APPENDIX C
Guidance, Standards, and Specifications for Referencing Coastal Navigation Projects, Hurricane Protection Projects, and Shore Protection Systems to National Water Level Observation Network Datums

C-1. Purpose

This Appendix provides guidance on evaluating and establishing vertical reference control on coastal navigation, hurricane protection, and shore protection projects. It describes preliminary evaluation actions necessary to determine if coastal navigation projects and related protective structures are adequately connected and modeled relative to the National Water Level Observation Network (NWLON) tidal datum and the National Spatial Reference System (NSRS) established by the Department of Commerce. For those projects that are not adequately connected to these reference systems, specific procedural actions required to effect this connection are outlined herein.

C-2. Applicability

This guidance applies to all projects in coastal areas that are referenced, modeled, designed, constructed, and maintained relative to a sea level datum. This includes all coastal navigation projects referenced to Mean Lower Low Water (MLLW) datum, and shore protection or hurricane protection projects referenced to MLLW, Mean Sea Level (MSL), Mean Tide Level (MTL), Mean High Water (MHW), or any other local tidal datum. It also applies to all projects that are not firmly referenced to a tidal datum determined relative to the National Water Level Observation Network (NWLON) network. To a limited extent, navigation projects in the Great Lakes and connecting channels are included. Navigation projects in non-tidal inland waterways are excluded.

C-3. Definitions

National Water Level Observation Network. The NWLON is composed of the continuously operating long-term primary and secondary control tide stations of the National Ocean Service. This Network provides the basic foundation for the determination of tidal datums for coastal and marine boundaries and for chart datum of the United States.

National Water Level Program. The NWLP, administered by the Department of Commerce, includes the NWLON and includes a database of water level elevation data and benchmark elevation data form historical long-term and short-term operated by that agency for various surveying and mapping projects.

National Tidal Datum Epoch. The specific l9-year period NTDE adopted by the National Ocean Service as the official time segment over which tide observations are taken and reduced to obtain mean values (e.g., mean lower low water, etc.) for tidal datums. It is necessary for standardization because of periodic and apparent secular trends in sea level. Special NTDEs are adopted for local areas with extreme relative sea level change due to significant land subsidence (Louisiana) or land rebound (SE Alaska) are partly based on a more recent 5-years of Mean Sea Level.

Mean High Water (MHW). The average height of all high waters at a place, covering a 19-year period. Heights of bridges over navigable waterways and legal coastal shoreline boundaries are typically referred to this datum. Coastal shorelines shown on navigation charts typically (but not always) depict MHW whereas depths on the same chart are referred to Mean Lower Low Water. Exceptions to this are found in Corps of Engineers inland navigation charts.

Mean Tide Level (MTL) and Diurnal Tide level (DTL). A plane often confused with LMSL that lies close to LMSL. MTL is the midpoint plane exactly between the average of MHW and MLW at a tide station. Hydraulic design manuals sometimes refer to MTL as being synonymous with Mean Sea Level. DTL is the midpoint exactly between the average Mean Higher High Water and Mean Lower Low Water.

Mean Sea Level (MSL) or Local Mean Sea Level (LMSL). The average height of the surface of the sea at a tide station for all stages of the tide, typically (but not always) covering a 19-year period which is usually determined from hourly height readings measured from a fixed and predetermined reference level.

Mean Lower Low Water (MLLW). The average height of the lower of the two low waters occurring in a day, at a tide gage over a 19-year period. Coastal navigation projects are referred to this datum. This datum superseded Mean Low Water (MLW) which was previously used as the navigation reference datum for the East Coast CONUS.

Mean Low Gulf (MLG). A low water tidal datum unique to Gulf Coast Districts, used as a navigation (and construction) reference datum in coastal waterways such as the Gulf Intracoastal Waterway (GIWW), the Mississippi River Gulf Outlet (MRGO). Derived from Mean Gulf Level.

Mean Gulf Level (MGL). A Gulf tidal datum established ca 1899 from which Mean Low Gulf (MLG) is derived and defined to this day. Presumed to be Mean Sea Level (MSL) at 1899 origin in Biloxi, MS.

Range of Tide. The difference in height between consecutive high and low waters. The mean range is the difference in height between mean high water (MHW) and mean low water (MLW) tidal datums. The great diurnal range or diurnal range is the difference in height between mean higher high water (MHHW) and mean lower low water (MLLW) tidal datums.

See NOS 2000 (Tide and Current Glossary) for additional definitions.

C-4. Scope

This guidance details the CEPD process for assessing the adequacy of referenced water level elevations on coastal projects. It provides technical options for correcting any determined deficiencies in existing project datums, including preparing programming budget estimates for implementing corrective actions. The primary emphasis is on navigation projects in that the evaluation of hurricane/shore protection projects (HSPP) will roughly parallel the flood protection structures covered in Appendix B. Guidance on hydrodynamic tidal modeling will be referenced to existing Corps publications—e.g., EM 1110-2-1100 (Coastal Engineering Manual).

C-5. General

The Corps uses a variety of water level datums to reference flood control, hurricane protection, navigation, and shore protection projects. Figure C-1 below depicts some of these reference planes. In coastal areas, and in coastal inlets, accurately modeling the sloping MLLW datum plane shown in the figure is the challenge. Additionally, the elevation of the actual water surface above the MLLW reference must be accurately measured in order to determine the elevation of a point relative to the MLLW datum. This water surface temporally varies due to tide, currents, wind, and other effects. On shore/hurricane protection projects, other sea level based datums may be required (e.g., MSL, MHW, MLW), along with their relationship to the NSRS (NAVD88).

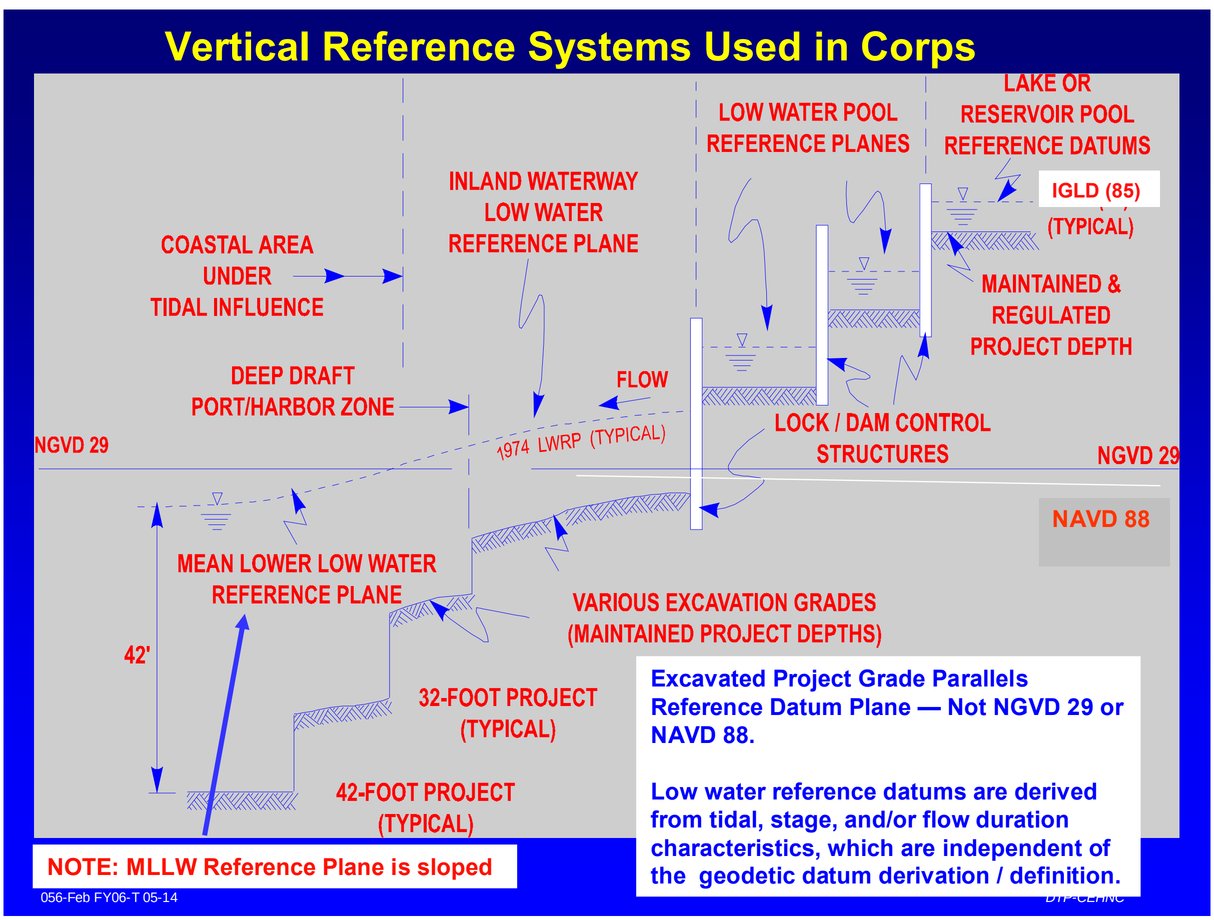

Figure C-1. Tidal and Inland Vertical Reference Datums

The overall effect of conditions at tidal inlets is best summarized in the following excerpt from EM 1110-2-1100 (Part II-6).

> "Hydrodynamic conditions at tidal inlets can vary from a relatively simple ebb-and-flood tidal system to a very complex one in which tide, wind stress, freshwater influx, and wind waves (4- to 25-sec periods) have significant forcing effects on the system … Flow enters the bay (or lagoon) through a constricted entrance, which is a relatively deep notch (usually 4 to 20 m at the deepest point). Entrance occurs after flow has traversed over a shallow shoal region where the flow pattern may be very complex due to the combined interaction of the tidal-generated current, currents due to waves breaking on the shallow shoal areas, wind-stress currents, and currents approaching the inlet due to wave breaking on adjacent beaches …. Particularly during stormy conditions with strong winds, flow patterns may be highly complex. Also, the complicated two-dimensional flow pattern is further confounded because currents transverse to the coast tend to influence the propagation of waves, in some cases blocking them and causing them to break … Final complications are structures such as jetties, which cause wave diffraction patterns and reflections. In inlets with large open bays and small tidal amplitudes, flows can be dominated by wind stress. In such cases, ebb conditions can last for days when winds pile up water near the bay side of the inlet, or long floods can occur when winds force bay water away from the inlet. Most inlet bays, however, are small and some are highly vegetated, so wind stress is not a dominant feature, except under storm conditions ... Although many bays do not receive much fresh water relative to the volume of tidal flow, substantial freshwater input due to river flow can sometimes create vertically stratified flows through a tidal inlet. Typically, however, well-mixed conditions exist for most inlets."

C-6. Requirements for Accurately Modeled Tidal Reference Datums

The need for accurate tidal datums on USACE projects surfaced in the IPET study following Hurricane Katrina, and is outlined in the beginning sections of this guidance document. Lack of accurate tidal datums can have significant impacts on project design and cost. For example, inadequately modeled navigation projects can result in millions of dollars of overdredging, along with increased construction disputes and claims. Erroneous reference datums on hurricane or shore protection projects can result in significant freeboard reductions.

Figure C-2 illustrates the impact of tidal elevation biases on dredging measurement and payment surveys. The tidal modeling bias in this single 1,600 ft acceptance section at Key West, FL resulted from tidal datum and phase errors, in addition to inherent survey biases. Minimizing these errors (and resultant construction costs) is a primary goal of this CEPD assessment.

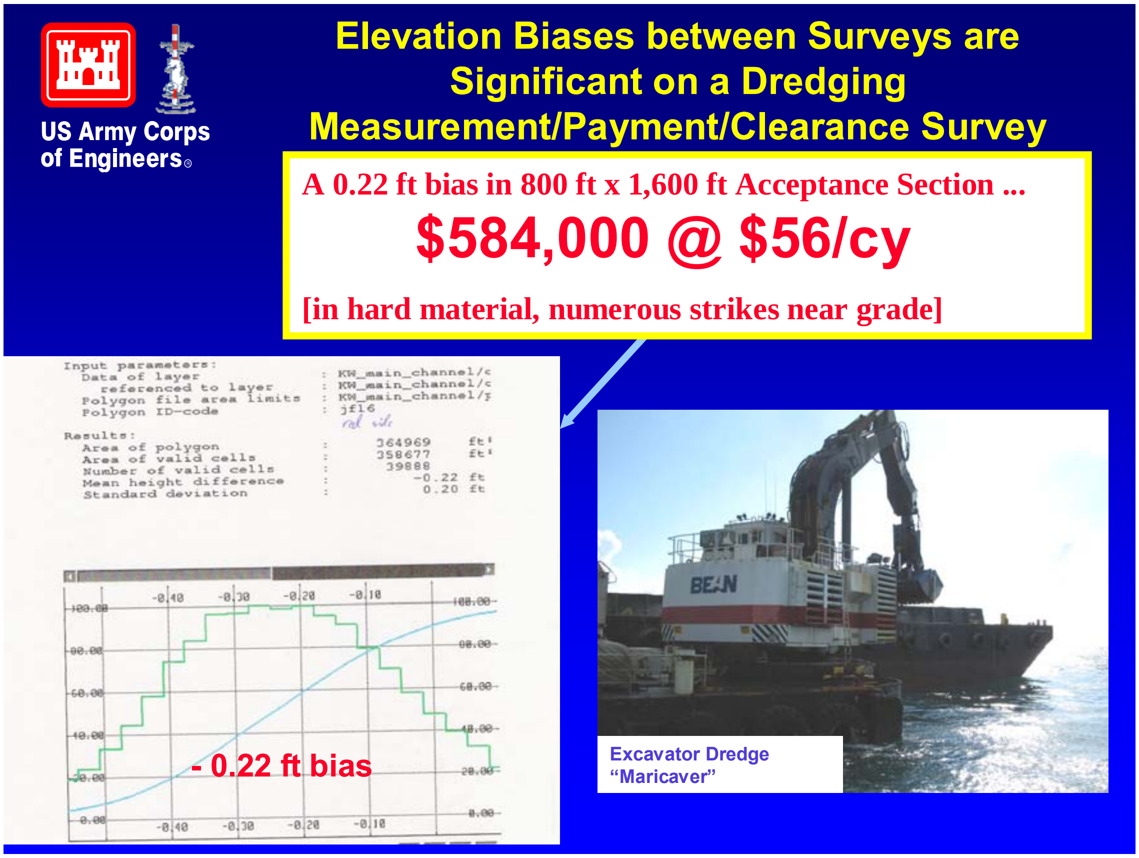

Figure C-2. Impact of elevation biases on measurement & payment

The primary factors that need to be considered in evaluating tidal datums include the following:

(1) Tidal phase variations over the project reach.

(2) Tidal range variations over the project reach.

(3) Tidal epoch adjustments for sea level or land subsidence changes.

(4) Quality of reference tidal gauge datum determinations

Tidal reference datums vary both spatially and temporally. Thus, the water surface elevation at a shore-based gauge is adequate only for that specific location and time. The height of the tidal wave will be significantly different between two points around an inlet, due to varying times and weather conditions. Likewise the MLLW datum will vary with the tidal range variations, which are modified by the topography of an inlet or coastal region. This MLLW datum cannot be extrapolated to another location without some modeled correction. It is also subject to long-term variation due to sea level rise, subsidence, or other factors. This requires periodic updating of tidal datums based on NOAA's latest National Tidal Datum Epoch (NTDE), which is currently 1983-2001 for most areas.

Current USACE practice for dredging and related payment surveys of navigation projects involves extrapolation of a water (tide) level gauge to the construction area. This assumes both the water surface level and reference datum range are constant over the extrapolated distance—i.e., assumes no tidal phase or range variations exist. This distance may range from a few hundred feet to over 10 miles. These assumptions of linearity in water surface levels and datum degrade with distance from the reference gauge. At low tidal ranges, longer extrapolations may be possible. At higher ranges (> 2 ft), extrapolations greater than ½ mile to 1 mile may be invalid and inaccurate. In addition, local weather conditions may further degrade the distance which a tide reading can be reliably extrapolated from a gauge. Sea surface setup due to strong winds can significantly alter the surface model. Approximate modeling methods ("tidal zoning") are used in some Districts, with mixed accuracy results—these methods do not account for local weather conditions. Figure C-3 depicts some of the geographical and physical factors that need to be considered in assessing the reliability of a tidal model for a coastal inlet project.

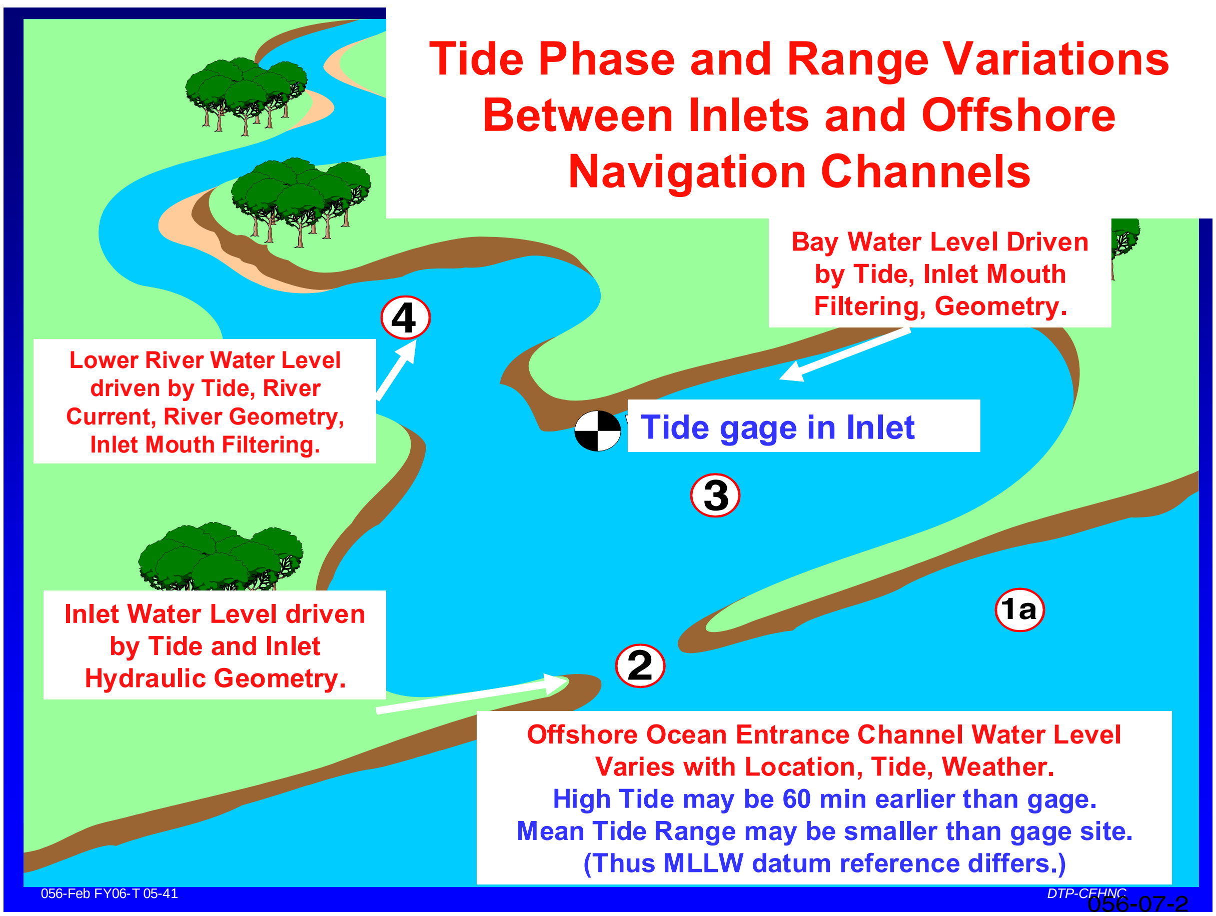

Figure C-3. Tide phase & range variations at an inlet

Figure C-4 from EM 1110-2-1100 (Part II-6, "Hydrodynamics of Tidal Inlets") clearly illustrates the tidal phase and range variation occurring between the ocean and bay at a typical coastal inlet.

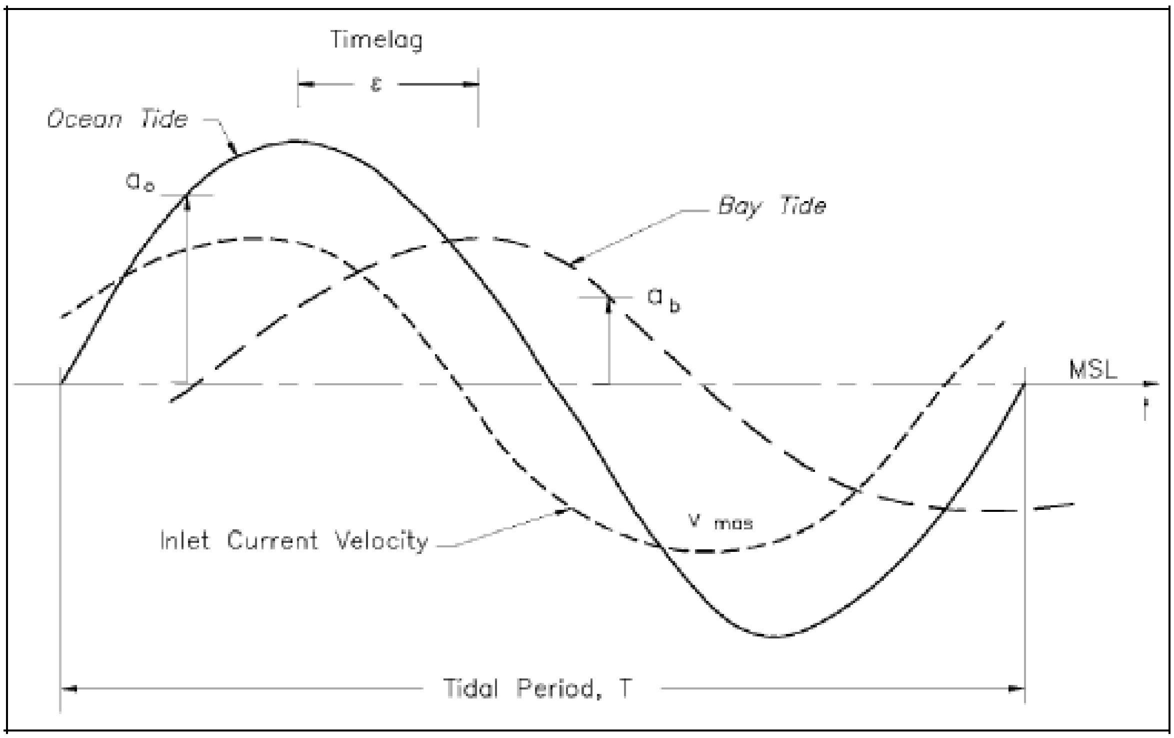

Figure C-4. Tide phase & range variations between ocean and bay from EM 1110-2-1100 (Part II), 30 Apr02

C-7. Tidal Phase Variations

The major error in the depth measurement of a navigation project is caused by tidal phase (time lag) variations between the gauge and the extrapolated location of the dredge or survey vessel at the project site. Local weather (winds) further varies the tidal profile in the region, as detailed in EM 1110-2-1100 (Part II-6). These phase and weather errors increase with the distance from the gauge and the topographic constrictions in an inlet. These systematic errors can exceed 1 to 2+ ft in moderate range projects—as depicted in Figure C-5. Most dredging measurement & payment disputes and claims arise over lack of adequate tidal phase modeling in a project. (See EM 1110-2-1003 for additional details on tidal phase errors.)

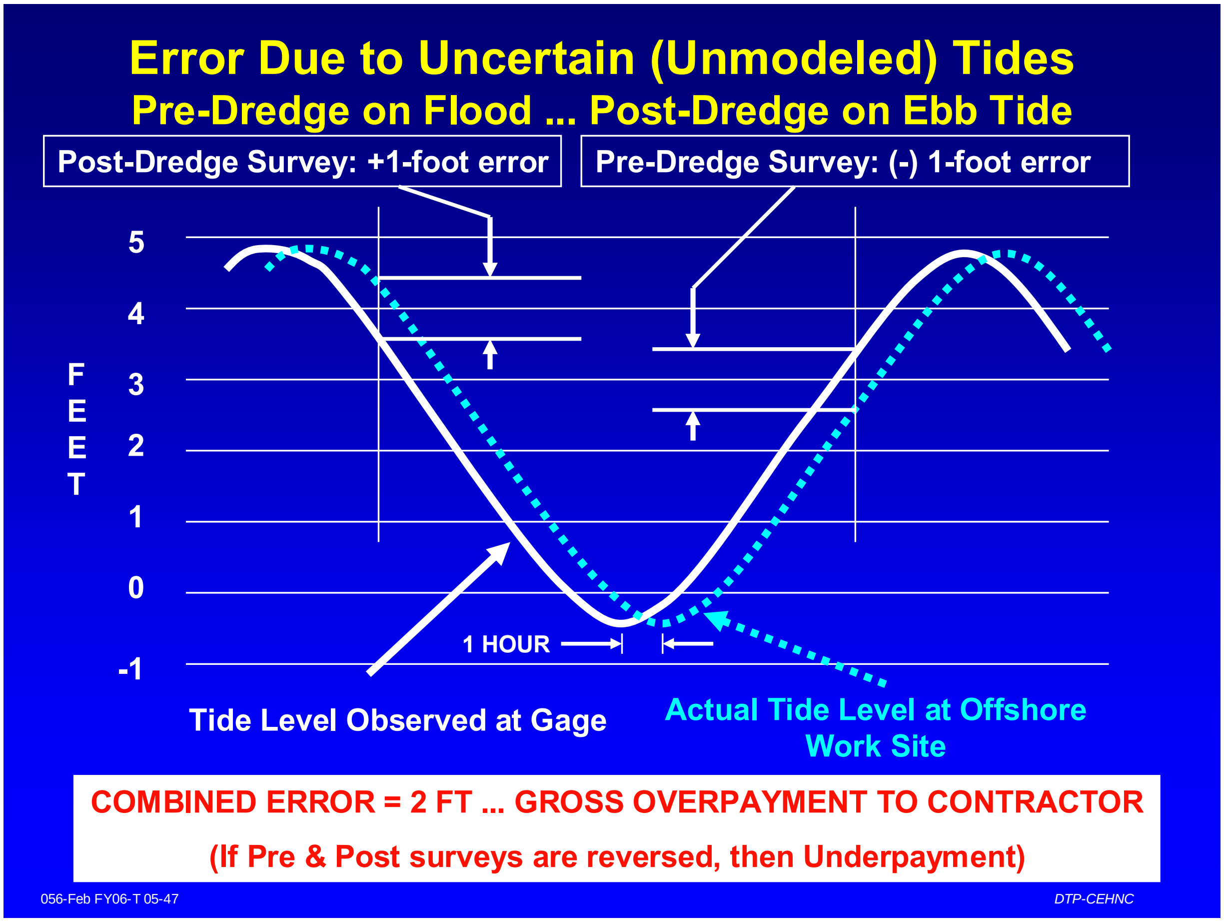

Figure C-5. Tide phase difference errors due to lag, wing, or other factors

Tidal phase lag errors (and weather/sea surface set up) are now effectively eliminated by using GPS-based surface elevation measurement techniques—i.e., RTK. USACE commands must endeavor to require RTK elevation measurement in lieu of tide gauge observations where tidal phase errors are significant. Figure C-6 illustrates the application of using GPS elevation measurement for removing tidal phase and wind-induced errors on a Jacksonville District dredging project at Key West, FL. In this example, a constant 0.3 ft bias is generated at a point only 3 miles distant from the gauge. This bias is significant given the tide range at this project is only about 2 ft. As shown in the figure, the RTK-determined elevation of the sea surface at the dredging site was accurate to approximately ±0.05 ft, which effectively minimized the tidal phase and weather errors. RTK operations are only successful if the MLLW to Ellipsoidal difference are correctly modeled and understood prior to the survey as these two reference planes have slopes relative to each other (see next section). This typically requires GPS survey connections to operating or historical tide station benchmarks.

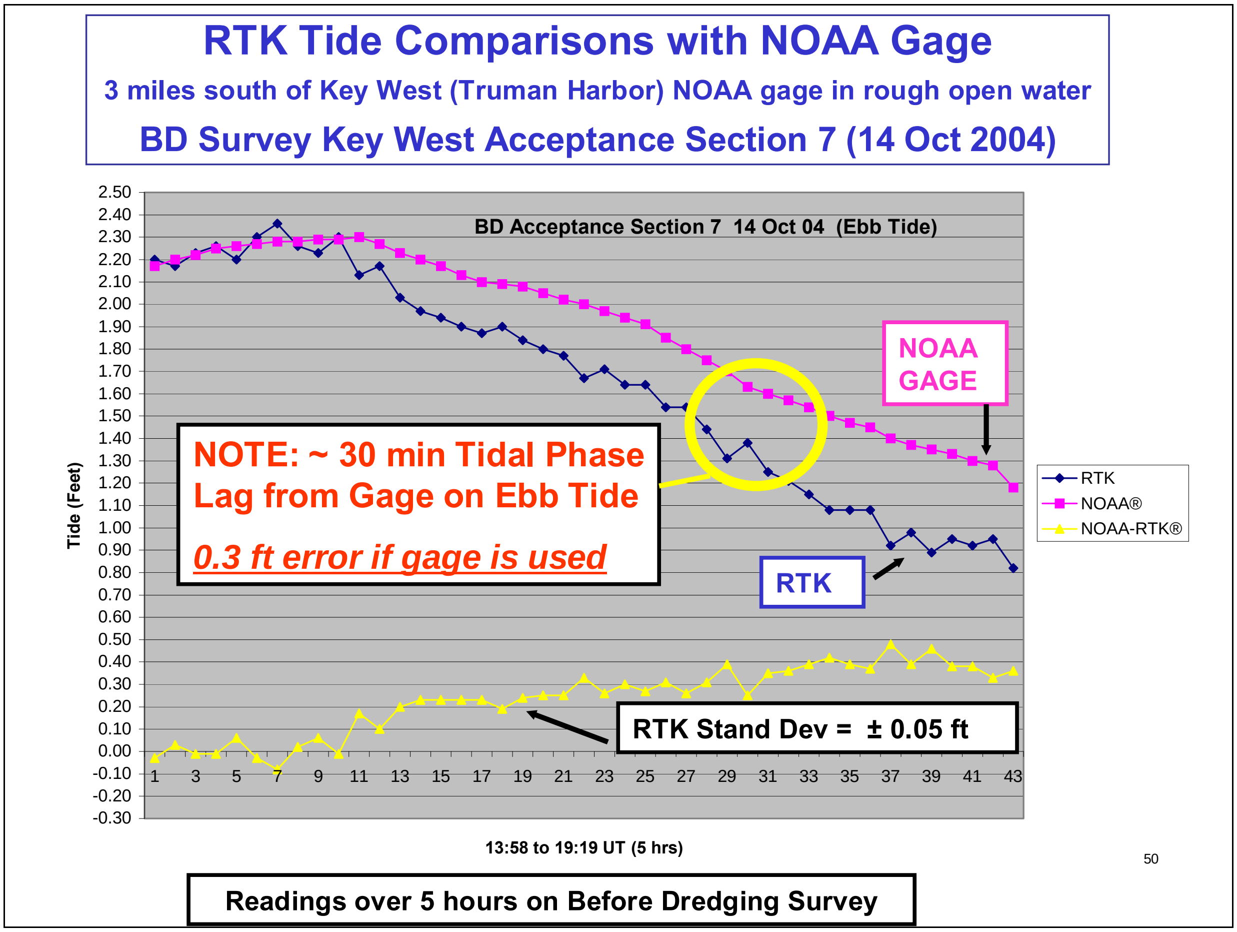

Figure C-6. Gauge v RTK comparisons

C-8. Tidal Range Variations

Variations in tidal range (i.e., undulations in MLLW datum relative to MSL or to geodetic datum) within a project must also be accounted for. This requires developing some model of the tidal hydrodynamic characteristics throughout the project.

Figure C-7 illustrates this MLLW variation over a Jacksonville District deep-draft coastal inlet project (St Johns River—Ocean to Jacksonville, FL). The MLLW datum relative to MSL varies from the ocean through the entrance jetties and up river. MSL also varies relative to NAVD88. The figure also depicts that NGVD29 and NAVD88 are not parallel datums. The MSL-MLLW datum variation may also be impacted by fresh water flow into the tidal area.

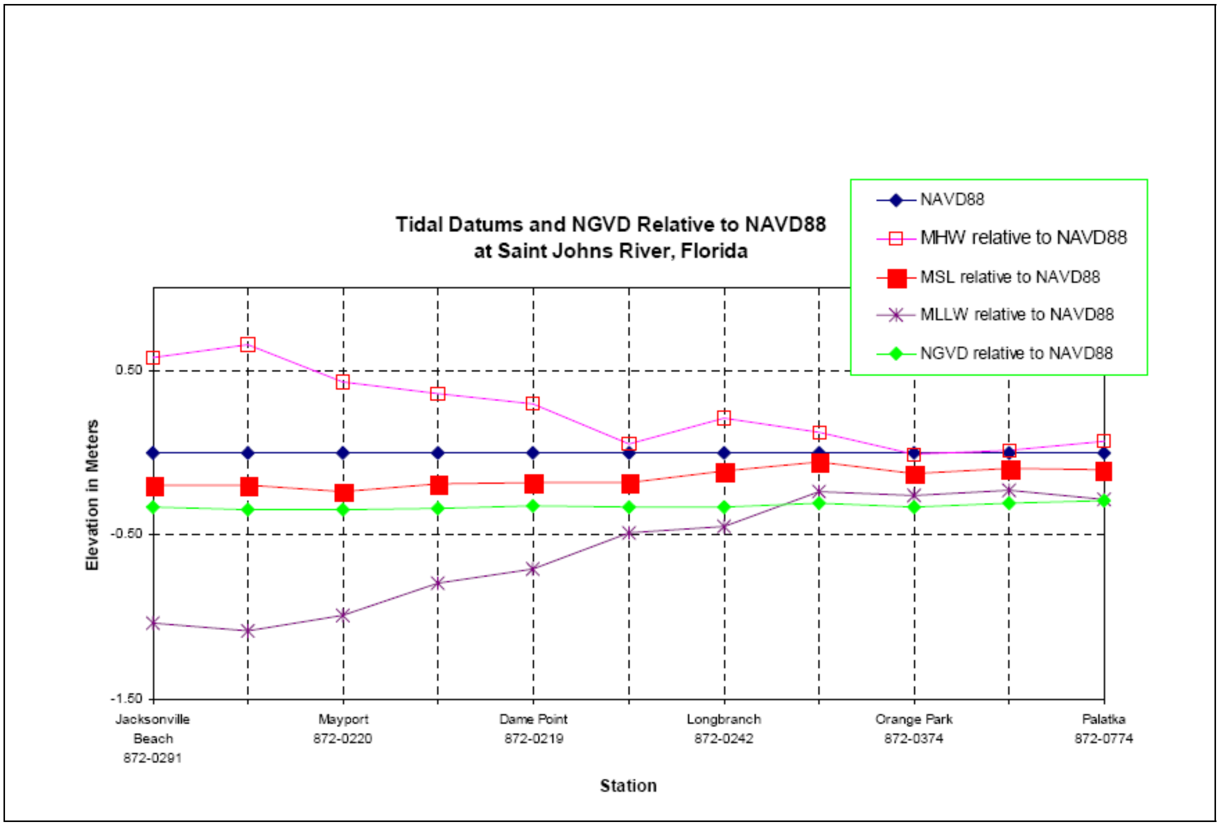

Figure C-7. Tidal range variation at a coastal inlet

Modeling the MLLW datum through a navigation project requires an adequate density of tide gauges from which the model can be calibrated, and intermediate datum variations between the gauges can be modeled. In the Figure C-7 above, the roughly 5.6 ft tide range at the ocean narrows down to 1.6 ft over a 25-mile navigation project. Although the gauges in the above figure are spaced at about every 5 to 10 miles, they should be of sufficient density to calibrate a hydrodynamic tidal model for this project. The lineal interpolations between the gauges shown on this figure represent only a crude tidal model of the MLLW reference plane—a full hydrodynamic tidal model would be represented by a smooth curve. In many cases with small tidal range variations, or with a dense gauge network, a linearly interpolated model may prove adequate. That may be the case for portions of the above project where the variation between gauges is not large.

Figure C-8 illustrates the tidal range variation over seven miles of a shallow draft project on the East Coast. There would appear to be a sufficient density of gauge data to model the MLLW datum plane for this project—including updating the older MLW and NGVD29 references shown in the figure.

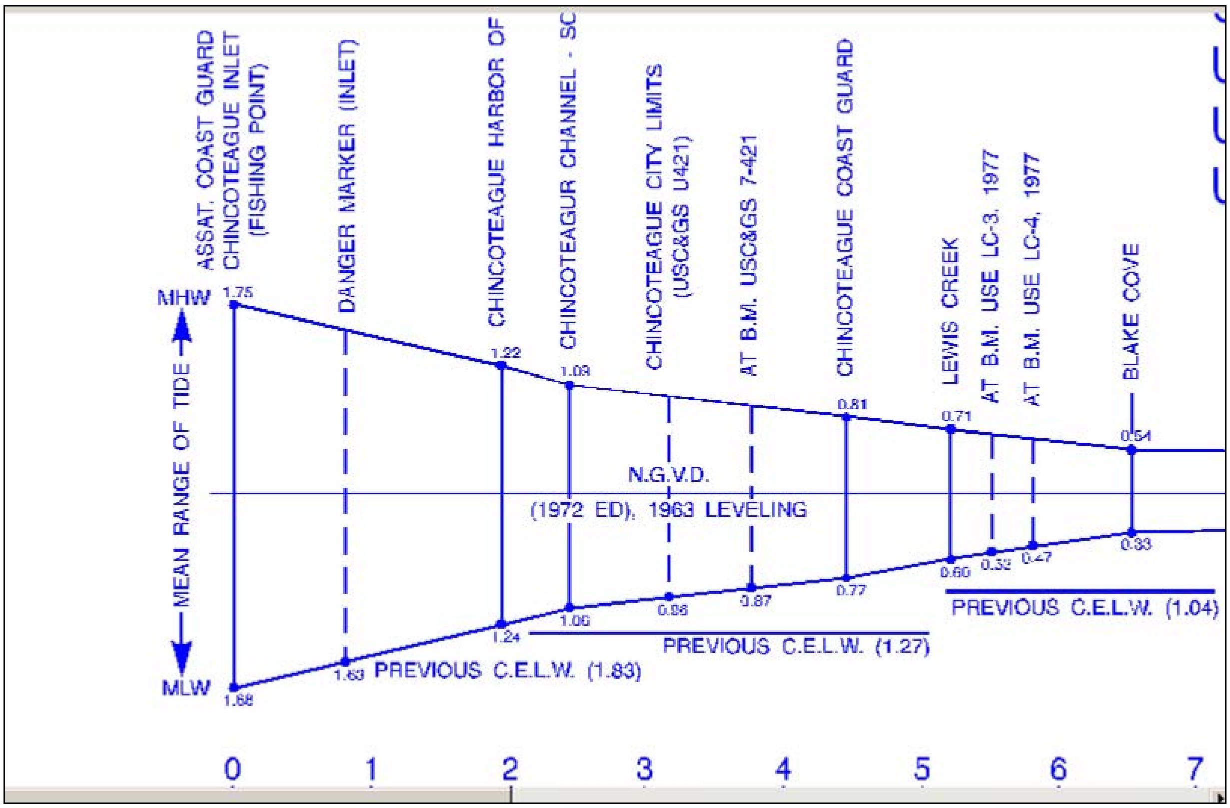

Figure C-8. Tidal range variation at Chincoteague Inlet, VA

C-9. Tidal Epoch Variations

NOAA periodically updates the tidal datums throughout CONUS and OCONUS to account for sea level rise, local land settlement, and other factors. These periodic adjustments can be significant—ranging from 0.2 ft to 0.5 ft over the last 19-year update period (1983-2001). Projects not updated since the 1940s would have significantly larger differences—see Figure C-9. These adjustments represent systematic changes to the local reference datum (e.g., MSL or MLLW). They also represent systematic biases in navigation project depths or hurricane protection project elevations. Typically, on most CONUS locations, the sea level rise results in maintaining deeper navigation projects than were authorized, and overdredging if the sea level rise is not accounted for. Conversely, on shore protection structures, sea level rise results in less protection than originally designed, assuming this predicted rise was not factored into the design.

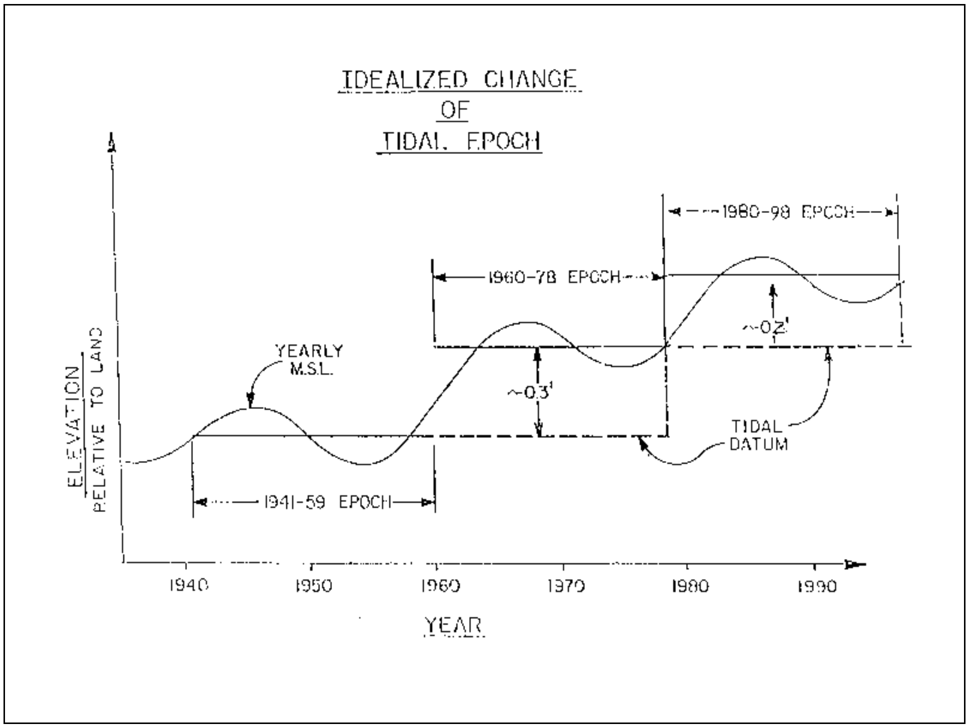

Figure C-9. Sea level rise 1940 to 1998 (Note that latest epoch is 1983-2001)

Tidal epoch adjustments are easily corrected by ensuring projects are updated when NOAA completes a periodic epoch change.

Figure C-10 illustrates the impact of a tidal epoch change on a project being dredged relative to the superseded 1960-1978 epoch. The adjustment to the latest epoch (1983-2001) significantly reduced the number of strikes above grade that would have required additional dredging.

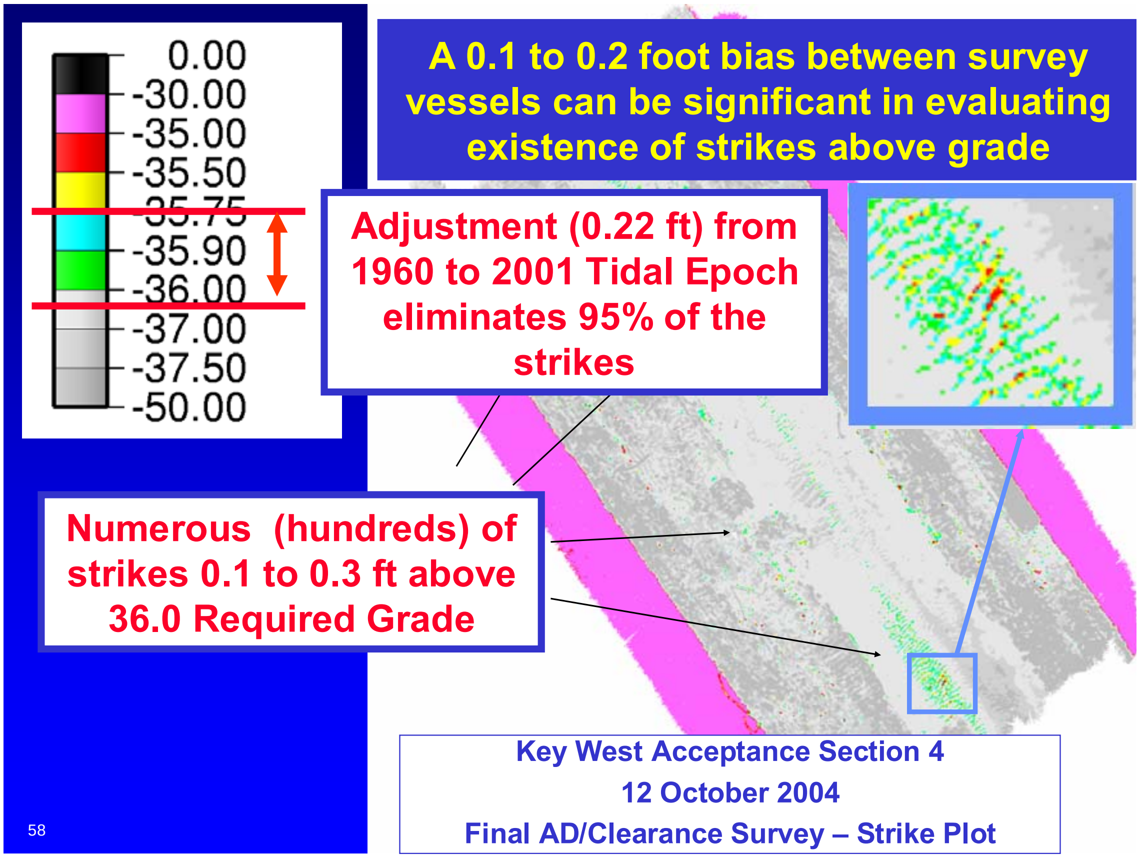

Figure C-10. Tidal epoch variation on dredging grade

Epoch updates are only averages from long term estimates. The adjusted sea level or MLLW datum elevation is based at the midpoint of the epoch. Thus the current epoch (1983-2001) is averaged about 1993. See NOAA 2001 and NOAA 2003 for additional details on the periodic computation and adjustment of tidal epochs.

C-10. Quality of Reference Tidal Gauge and Computed Water Level Datum

The MLLW datum at a gauge site (either existing or historic) must be adequately connected with the NOAA NWLP network. This implies using either a NOAA gauge site that is on or is connected with the NWLP, or a locally operated gauge that meets with NOAA connection specifications. Isolated benchmarks (those of USACE or any other agency) that purport MLLW or MSL reference elevations should be considered highly suspect unless their connection with a NWLP gauge site can be firmly established (i.e. direct differential level or static GPS connections to a NOAA tidal benchmark). Any such marks must also contain an epoch designation attached to their elevation that signifies it has been adjusted to the current tidal epoch. For example, the elevations at a benchmark should have, at minimum, the following type of metadata in order to be considered acceptable as a reliable reference for controlling USACE projects:

Benchmark: USED INLET 1957
Elevation: 8.29 ft (NAVD88 [adjustment epoch as appropriate])

Elevation: 7.21 ft (above MLLW—1983-2001 epoch)
Source: [specify NGS "PID" or NOAA CO-OPS tide station designation number]

USACE benchmarks set near NOAA gauges should be leveled in using standard 3rd Order survey procedures. These marks should be entered into the NSRS if they are going to be used as a primary vertical control point for the project—e.g., setting a tide calibration staff or as a RTK base.

If a complete tidal-geoid model has been developed for a project, then this model designation—and date—should also be included as primary metadata with a benchmark used to control construction dredging.

When in doubt about the quality of an existing USACE benchmark, always hold to gauges/benchmarks published on the NOAA reference network—either currently operating or historical.

C-11. Requirements to Reference Coastal Navigation Projects to MLLW Datum

Some USACE projects are still defined relative to non-standard or undefined reference datums (e.g., Mean Low Gulf, Gulf Mean Tide, MSL, NGVD, MLW, etc.). In accordance with the intent of Section 224 of WRDA 1992 (33 U.S.C 562) and The National Tidal Datum Convention of 1980 (NTDC 1980), navigation projects (channel depths and dimensions) in coastal tidal areas must be defined relative to the MLLW. This WRDA 92 amendment to Section 5 of the Rivers and Harbors Appropriation Act of 1915 overrides and supersedes previously authorized reference datums, and specifically directs that the datum defined by the U.S. Department of Commerce be used.

> *Section 5 of the Act of March 4, 1915 (38 Stat. 1053; 33 U.S.C. 562), is amended -- (as indicated). "That in the preparation of projects under this and subsequent river and harbor Acts and after the project becomes operational, unless otherwise expressed, the channel depths referred to shall be understood to signify the depth at mean lower low water as defined by the Department of Commerce for nautical charts and tidal predictions in tidal waters tributary to the Atlantic and Gulf coasts and at mean lower low water as defined by the Department of Commerce for nautical charts and tidal predictions in tidal waters tributary to the Pacific coast and …"*

As previously stated, the MLLW reference plane is not a flat surface but slopes as a function of the tidal range in the area. Tidal range can increase or decrease near coastal entrances; thus the MLLW must be accurately modeled throughout the navigation project. The required grade at all points on the navigation project is dependent on tidal modeling--requiring determination of the elevation of the MLLW datum plane from a series of gauge and/or modeled observations at each point. Guidance on performing this conversion was first issued as ETL 1110-2-349 on 1 Apr 93 *(Requirements and Procedures for Referencing Coastal Navigation Projects to Mean Lower Low Water Datum).* This guidance was subsequently incorporated into engineering manuals—EM 1110-1-1005 and EM 1110-2-1003 and is also included as an appendix in the IPET 2006 Report.

C-12. Accuracy Standards for Tidal Datums

The total error of tides and water levels for application to hydrographic surveys can be considered to have component errors of:

(1) the measurement error is a combination of the gauge/sensor and processing error to refer the measurements to station datum. The measurement error, including the dynamic effects of waves and currents, should not exceed 0.10 m at the 95% confidence level. The processing error also includes interpolation error of the water level at the exact time of the soundings (water levels are recorded every 6-minutes). An estimate for a typical processing error is 0.10 m at the 95% confidence level.

(2) the error in computation of equivalent 19-year tidal datums from short term tide stations. The shorter the time series, the less accurate the datum, i.e. the larger the error. The closer the subordinate station is in geographic distance and in tidal difference to a control station, the more accurate the datum. Estimated maximum errors of an equivalent tidal datums based on one month of data is 0.08 m for the Atlantic and Pacific coasts and 0.11 m for the coast in the Gulf of Mexico (at the 95% confidence level).

(3) the error in application of tidal zoning. Tidal zoning is the extrapolation and/or interpolation of tidal characteristics from a known shore point(s) to a desired survey area using time differences and range ratios. The greater the extrapolation/interpolation, the greater the uncertainty and error. These are correlated with geographic distance and the difference in tidal characteristics. Estimates for typical errors associated with tidal zoning are 0.20 m at the 95% confidence level. However, errors for this component can easily exceed 0.20 m if tidal characteristics are very complex, or not well defined, and if there are pronounced differential effects of meteorology on the water levels across the survey area.

For both (2) and (3) above, the tidal difference is a function of the difference in time of tide, range of tide, and type of tide (shape of the tide curve).

(Note that the use of RTK elevation measurement, coupled with a fixed MLLW datum model, effectively minimizes or eliminates the above errors.)

Datum Error:

Refer to NOS 2001 (Tidal Datums and Their Applications) for more details. The following table from this reference illustrates the accuracy of tidal datums for various lengths of record.

Table 2. Generalized accuracy of tidal datums for East, Gulf, and West Coasts when determined from short series of record and based on +/- sigma. From Swanson (1974).

Series Length (months)	East Coast (cm)	(ft.)	Gulf Coast (cm)	(ft.)	West Coast (cm)	(ft.)
1	4.26	0.13	5.91	0.18	4.26	0.13
3	3.28	0.10	4.92	0.15	3.61	0.11
6	2.30	0.07	3.94	0.12	2.62	0.08
12	1.64	0.05	2.95	0.09	1.97	0.06

The above table indicates that in general, tide stations with at least 3 months record have determined a datum to within ± 0.2 ft. If a NOAA historical gauge has some 12 months of record (which is typical) then the accuracy of the computed MLLW datum at that point is around ± 0.1 ft at 95%.

These maximum estimates are no longer being used operationally by NOS to estimate datum uncertainties from tide stations. Instead of the regionalized approach in the above table, the following relationships are being used to estimate tidal datums for each individual subordinate tide station. Specifically, the tidal datum uncertainty is determined from the relationship of the subordinate tide station to the control tide station to which the simultaneous comparison is being made (NOS 2003). Assuming most subordinate tide stations for NOS hydrographic surveys are operated for less than one-year durations, the Bodnar regression equations for mean low water for one-standard deviation ("s") estimates are of the form:

$$s_{1\ \text{month}} = 0.0068\ \text{ADLWI} + 0.0053\ \text{SRGDIST} + 0.0302\ \text{MNR} + 0.029$$

$$s_{3\ \text{months}} = 0.0043\ \text{ADLWI} + 0.0036\ \text{SRGDIST} + 0.0255\ \text{MNR} + 0.029$$

$$s_{6\ \text{months}} = 0.0019\ \text{ADLWI} + 0.0023\ \text{SRGDIST} + 0.207\ \text{MNR} + 0.030$$

$$s_{12\ \text{months}} = 0.0045\ \text{SRSMN} + 0.0128\ \text{MNR} + 0.025$$

where:

ADLWI is the absolute difference (in hours) in low water time intervals between subordinate and control stations.

SRGDIST is the square root of the geodetic distance between the control and subordinate stations, measured in nautical miles.

MNR is the mean range ratio that is computed from the absolute value of the difference in mean range of tide between control and subordinate tide stations divided by the mean range of tide at the control station.

SRSMN is the square root of the sum of the mean ranges computed by adding the mean ranges of the control and subordinate stations and then taking the square root of this sum.

For stations with series longer than one-year in length the datum errors can be time- interpolated between the estimate at that station for a one-year series and the zero value at 19 years. Errors in tidal datums for accepted datums from 19-year control tide stations are zero by definition.

Using these formulas, estimates of the datum error can be uniquely computed in the planning process for each subordinate tide station being used for the hydrographic survey using historical and accepted tidal datums on file.

Tidal Zoning Error:

Discrete tidal zones are constructed based on knowledge of the tide at shore-based historical stations and estimated positions of co-tidal lines for range and time of tide. For most NOAA applications the resolution of the zoning has been to construct a zone polygon for every 0.2-foot change in range and every 0.3-hour change in time of tide. For many tidally complex areas (such as around Key West for instance) tide zones with higher resolution are used. Tidal zoning errors are considered random errors although they have a certain periodic nature and not a normal statistical distribution. Zoning errors also are characterized by two components: a time correction and a range ratio correction to observations from a nearby tide station. Maximum zoning errors for each project are estimated by simultaneously comparing tide curves constructed from time and range corrections to historical tide station observations. Statistics of the residuals are then analyzed to estimate the error in the zoning for the entire project.

Zoning	Estimate	Error Type
Typical Areas	~ 0.10m	s - random
Complex Areas	~ 0.20m	s- random

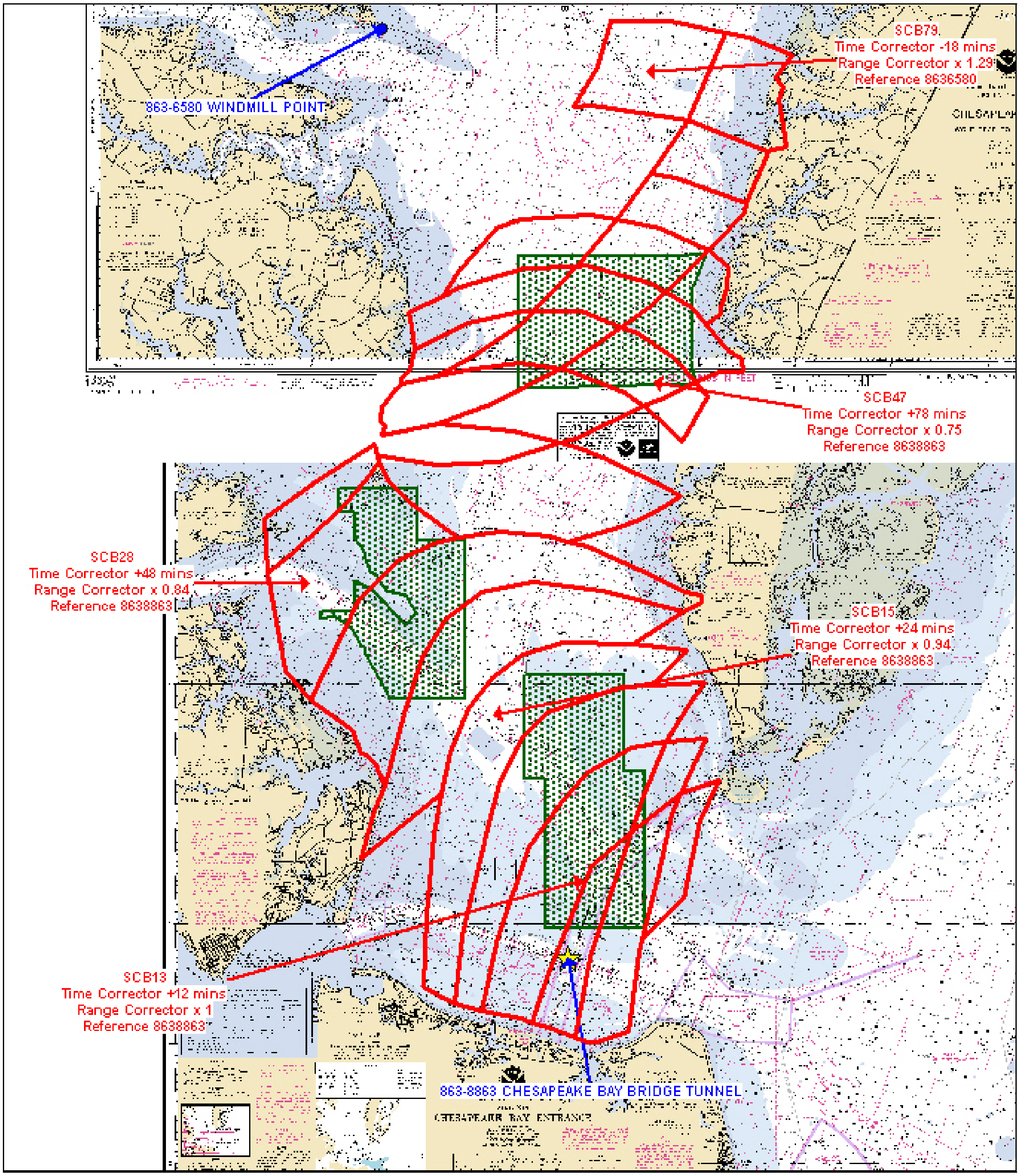

Figure C-11. The discrete tidal zones constructed from the co-tidal lines and the survey areas in lower Chesapeake Bay

There are inherent errors in application of discrete tidal zoning: 1) discontinuities at the edge of the zones; 2) resolution in areas of complex tidal characteristics, where the location and number of zones is not adequate to describe the changes in the tide over the survey area; 3) where large time corrections and large range ratios are required; and 4) the fact that placement of the zones becomes subjective when the co-tidal lines are based upon inconsistent or inadequate source data.

Figure C-11 above illustrates an application for tidal zoning in Chesapeake Bay—in particular for areas in the middle of the bay where no RTK or VRS coverage is available. Where RTK/VRS coverage is available only the corange model would have application.

<u>Discussion of Applications to CEPD:</u>

The major contributors to the tides error budget are the datum error which contributes as a systematic bias and the tidal zoning error which contributes as a random error. In practice the datum error is reduced with longer data series. Errors can be very significantly if less than 30-days of data are observed. Substantial reductions in error from those of a 30-day series are not realized until one-year of data are collected. For CEPD tidal modeling purposes, NOAA gauge datums, (or acceptable datums from another agency's long-term gauges) will be assumed as absolute—no effort will be considered in improving the accuracy of existing datums by extending gauge periods. The tidal zoning error can be reduced by lessening the amount of time and range correction needed by establishing more tide stations for use in direct control of the survey. Use of the Tidal Constituent and Residual Interpolation (TCARI) (discussed in later sections on models) can also reduce tidal zoning errors. Project planning an implementation are focused on finding the practical balance between the number of tide stations required and the amount of tidal zoning required. This in turn depends upon the complexities of the tidal characteristics in the area and the resources and logistics required to establish and maintain tide stations. Calibrated tide gauges that are configured and installed to minimize dynamic errors result in the measurement errors usually being minor contributors to the tides error budget. The estimated total tides error can then be root-summed-squared with all of the other hydrographic survey error sources to estimate the total survey error budget.

As stated above, for USACE tidal modeling purposes, and subsequent maintenance dredging and construction of projects, the accuracy of a NOAA gauge datum, (or acceptable datums from another agency's long-term gauges) will be assumed as absolute—i.e., they will be assumed to have “zero error.” This assumption is valid in that the final developed MLLW-geoid model will also be considered fixed, and containing minimized errors based on the developed model. This fixed model, when used with RTK, provides near absolute repeatability between users (surveyors, dredges, etc.), limited mainly by the precision of the RTK solution and the site calibration. This repeatability is critical for equitable dredge payment surveys. If RTK is not used, and zoning estimates relative to a water level gauge are used, then repeatability will be dependent on all the errors discussed in the above paragraphs. Future events (i.e., updated epochs, major projects construction or deepening, etc.) will require periodic modifications to the tidal model; however, these will be few and far between—perhaps only every 19 years.

<u>USACE EM 1110-2-1003 Accuracy Standards:</u>

USACE hydrographic surveying accuracy standards for water surface accuracy are defined in Table 3-1 of EM 1110-2-1003 (Hydrographic Surveying)—excerpted below.

EM 1110-2-1003 Table 3-1. Minimum Performance Standards for Corps of Engineers Hydrographic Surveys (Mandatory)

PROJECT CLASSIFICATION		Navigation & Dredging Support Surveys Bottom Material Classification Hard	Soft	Other General Surveys & Studies (Recommended Standards)
RESULTANT ELEVATION/DEPTH ACCURACY (95%)				
System	Depth (d)			
Mechanical	(d<15 ft)	± 0.25 ft	± 0.25 ft	± 0.5 ft
Acoustic	(d<15 ft)	± 0.5 ft	± 0.5 ft	± 1.0 ft
Acoustic	(15>d<40 ft)	± 1.0 ft	± 1.0 ft	± 2.0 ft
Acoustic	(d>40 ft)	± 1.0 ft	± 2.0 ft	± 2.0 ft
MAXIMUM ALLOWABLE BIAS		± 0.1 ft	± 0.2 ft	± 0.5 ft
WATER SURFACE MODEL ACCURACY		[½ depth accuracy standard]		½ depth accuracy

EM 1110-2-1003 Section 3-12. Tidal or Water Level Surface Modeling Accuracy

These standards refer to the accuracy by which the water surface elevation is determined at the point a depth measurement is observed. Tide or stage uncertainty can often be the major error component in the resultant accuracy of an elevation measurement. It includes the precision which a tide or river stage is interpolated or extrapolated (i.e., modeled) relative to a reference gauge. In areas where modeling techniques are inadequate, where the project area is distant from the reference gauge, or with large tidal range and phase variations, carrier-phase DGPS techniques may be necessary to meet the required standard.

The above table was developed before RTK methods were readily available, and assumed that water surface elevations were directly extrapolated from the nearest gauge—i.e., no tidal model, no tidal zoning, etc. The maximum allowable bias standard is the governing criteria for survey accuracy (or actually repeatability). This bias is derived from repeated surveys over the same area (Performance QA Tests) as outlined in Chapter 11 of EM 1110-2-1003. Meeting this bias standard becomes difficult or impossible if tidal phase errors are not compensated. The “1/2 depth accuracy” standard in the table needs to be updated in accordance with the revised accuracy criteria in the next section of this guidance document. Depth accuracy standards in EM 1110-2-1003 Table 3-1 range from ± 0.25 ft to ± 2 ft, depending on depth and type of bottom; thus, the intended water surface model accuracy ranges from ± 0.1 ft to ± 1 ft. Accuracies well within these limits can be achieved by (1) using RTK elevation measurement (including geoid modeling), and (2) hydrodynamically modeling and calibrating the tidal MLLW datum relative to local NOAA gauges.

C-13. Accuracy of a Tidal-Geoid Model of a Navigation Project

Table C-1 below represents the desired accuracy of a navigation project model, considering both the MLLW datum and the geoid.

Table C-1. Recommended Accuracies for Reference Datums on Navigation Project Tidal Models

	Accuracy (95%)	Reference Datum
Absolute accuracy of tidal-geoid model	± 0.25 ft (± 8 cm)	MLLW
Relative accuracy of tidal-geoid model	± 0.1 ft (± 3 cm)	MLLW
Tidal-geoid model resolution	0.01 ft	
Linear density along navigation channel	100 to 500 ft (varies with magnitude of tidal range)	
Geoid model	use latest available at time of study (currently Geoid 03)	
Accuracy of predicted geoid model	< 5 cm	
Accuracy of predicted MLLW datums In offshore entrance channels	< 5 cm	
Tidal-geoid model format	1D or 2D (typically 1D for linear navigation channels)	

NOTE: The above standards are believed representative for most CONUS navigation projects. Exceptions may exist in extreme tide ranges or in parts of Alaska.

In general, a full tidal-geoid model absolute accuracy of ± 0.25 ft should be achievable at most deep-draft navigation projects where NOAA calibration gauge data exists. Local (relative) model accuracy should be better than ± 0.1 ft on such a project—i.e., that accuracy relative to one or more local NOAA gauges. Regardless of the resultant absolute accuracy of a tidal model for a region, the relative accuracy is most critical. For navigation projects, dredging measurement and payment performed using RTK methods will typically employ a combined tidal-geoid model from which to correct observed ellipsoid heights measured at the water surface. Thus, the measured ellipsoidal elevation of the water surface at any point is corrected for (1) geoid undulation from the reference benchmark, and (2) tidal range (MLLW) variations from the reference benchmark based on hydrodynamic models of the tide in the region—see Figure C-12. The actual offshore water surface level above corrected MLLW is thereby measured at every observation (1 to 10 Hz) made by a survey vessel, dredge, or commercial vessel employing RTK methods; and an average surface level (or tide) computed using filters and/or an IMU. As long as every user (vessel) employs the same tidal-geoid model for the region, then full repeatability of surface elevation measurements will be achieved. The relative accuracy of the RTK measured surface elevation and tide level will typically fall around ±0.05 ft, regardless of the user. The tidal-geoid model developed for the project is considered as absolute.

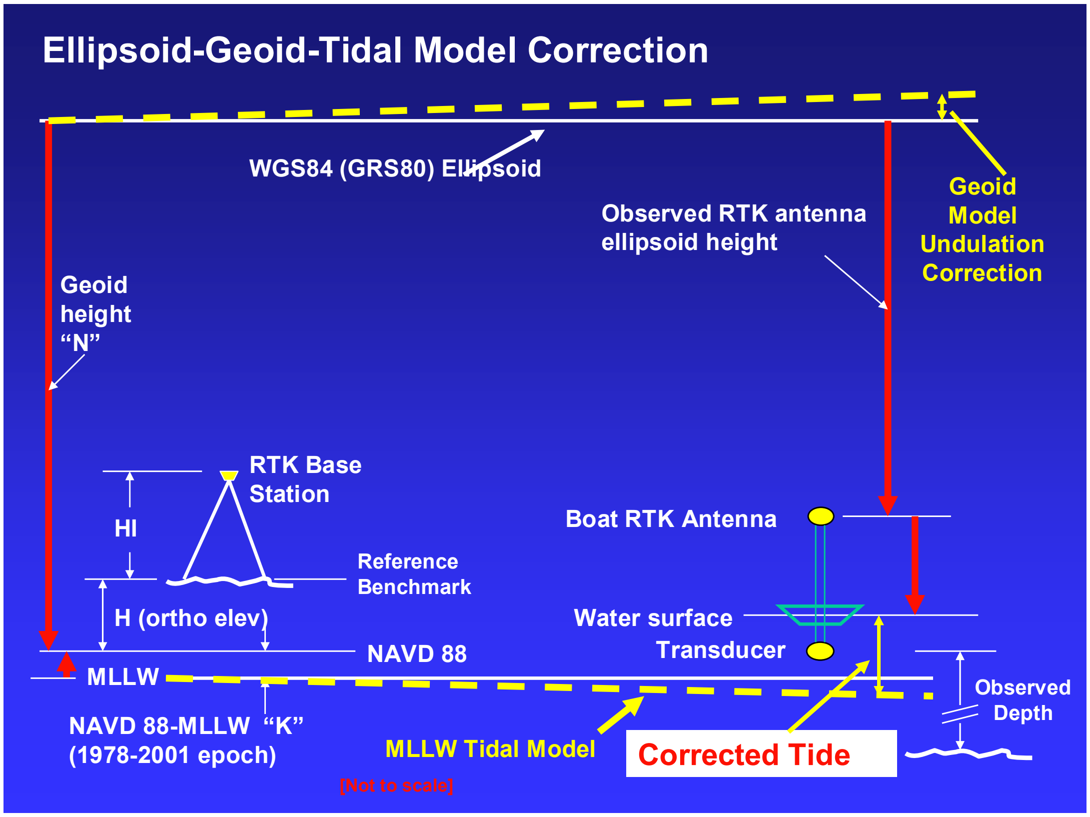

Figure C-12. RTK Tidal-Geoid model corrections for navigation projects

Geoid model accuracy is a function of the location and density of NSRS vertical control and gravity data in the area. The predicted geoid undulation from the latest model will be used for offshore entrance channels, areas which obviously have no vertical control but have been estimated using other techniques (airborne gravity). Those modeling the project should check with NGS to confirm the accuracy of the predicted model does not exceed reasonable tolerances. Likewise, the predicted tidal range in offshore entrance channels 3 to 10 miles seaward may have to be based on established regional models of the ocean tides. In such cases, the estimated accuracy of these regional models may be verified by contacting ERDC/CHL or NOAA. Alternatively, these offshore tidal ranges (and indirectly, the geoid model) can be easily confirmed by observing long-term RTK data recorded during the course of a survey in the area—reference Jacksonville District 2005.

It is emphasized that the tidal-geoid model developed for each project must be published and disseminated to all users. This may be a simple ASCII file, or in the form of a "KTD" file used by commercial navigation dredging software (HYPACK, Inc.). Since most USACE navigation projects are linear, only a 1D model is required—e.g., a tidal-geoid correction every 100-ft station down the channel centerline. This is adequate to cover the areal extent of a 100 ft to 1,000 ft wide channel. This file may periodically be updated if the geoid model is significantly modified by NGS. Thus, the file must clearly identify (metadata) the source of the data. Care must be taken in that in some navigation/dredging processors, the geoid correction may be performed separately (by the GPS receiver) from the MLLW tidal model correction—i.e., two distinct corrections. Thus the KTD file may contain only the tidal datum correction (K) or both the tidal datum correction (K) and the geoid correction (N). Users must also be advised that RTK, like any measurement system, must be periodically checked (and site calibrated/localized if necessary) against a physical recording gauge or staff gauge.

C-14. Corrective Options for Navigation Projects Requiring MLLW Datum Upgrades

A number of options exist to update a tidal model for coastal navigation projects that are found to be deficient and require upgrading. Updating the tidal model requires the following basic actions:

(1) Ensure tidal datum reference planes (MLLW) are defined relative to published NOAA gauges and tidal benchmarks.

(2) Ensure the latest tidal epoch adjusted by NOAA is used.

(3) Model the MLLW reference plane and geoid throughout the length of the project.

(4) Publish and disseminate the tidal-geoid model for users.

(5) Optionally develop the NAVD88-MLLW datum relationship at tidal benchmarks.

(6) Submit any hydrodynamic modeling data to NOAA for their use in expanding the nationwide VDatum.

Items (1) and (2) above are easily achieved as long as an existing or historical gauge exists at the navigation project. This will likely be the case for the majority of the Corps' deep-draft navigation projects. If not, then a standard gauging program will have to be developed in order to establish a tidal datum at a project—see NOS 2003, "Computational Techniques for Tidal Datums Handbook." Any such effort must be coordinated with NOAA in order to ensure the project becomes included in NOAA's NWLON inventory. Time and cost estimates for performing the gauging can be obtained from NOAA.

Project modeling—Items (3) through (6) above—will require close coordination with District H&H elements, ERDC/CHL, and/or NOAA. In small tide ranges either between gauges or in the overall area, lineal interpolation of the MLLW model will often be sufficiently accurate and economically developed. These models may already have been developed for some projects, and may currently need only to be adjusted for tidal epoch updates and geoid models.

C-15. Modeling the MLLW Datum on Navigation Projects

As stated earlier, a number of techniques can be employed to model the MLLW datum on a navigation project. These range from extrapolating the MLLW datum from a single gauge to a full hydrodynamic model. Various options include:

- Small project and small tide range ... no model required, use gauge MLLW elevation extrapolated throughout project area
- VDatum model--check with NOAA CSDL if VDatum model exists or is planned
- Interpolated (simple linear or discrete tidal zoning) model between gauges
- TIN model ... MicroStation InRoads
- TCARI model ... TCARI Spatial Interpolation Tool
- Hydrodynamic model

Most often, linear or surface interpolations between gauges will be used.

On projects with larger tide ranges where the uncertainty of a linear model between gauges increases beyond the allowable tolerance, a more sophisticated hydrodynamic model may be required to best define the MLLW datum. This presumes adequate gauge records exist from which to calibrate the tidal model in an area. On some projects, a single gauge may be adequate. Others may require additional gauges to define the model. If these additional gauges do not exist, then a gauging program will have to be programmed. In addition, topographic and bathymetric models of the project may have to be generated if they do not exist. A firm connection to the orthometric datum (NAVD88) may also be required. Thus, a number of project-specific technical factors will govern the overall effort required to model the MLLW datum plane of a project. This will also include the experience of those assessing the tidal model relative to the required relative accuracy of the tidal model.

One must not lose sight of the overall error budget in evaluating the effort required to model the MLLW datum on a project. Relative to removing large phase and wind setup errors with RTK measurements, these MLLW datum modeling errors are often insignificant. Thus, before embarking on any extensive (and costly) gauging program, the significance or sensitivity of these added gauge observations on the overall tidal model must be substantiated. Likewise, the difference between a simple lineal interpolation and a hydrodynamically modeled interpolation must be evaluated for significance relative to the intended tolerance.

In addition, there is no point in performing elaborate MLLW datum tidal modeling unless RTK surface elevation measurements are mandated for the completed project. Having a MLLW tidal model accurate to ±0.1 ft with a ±1 ft phase error due to extrapolated gauge readings five miles offshore would obviously be an inconsistent use of resources.

Figure C-13 illustrates a typical modeling requirement for a coastal inlet navigation project. This project may currently be referenced to an unknown MLW or MLLW datum, is not referenced to local NOAA tide gauges, or has not been updated to the latest tidal epoch. As shown, the existing model is based on a straight-line interpolation between the gauges (assuming NOAA gauges were originally used). The MLLW variation is then interpolated, typically at 0.1 ft increments along the channel, as indicated by the stair-step in the figure. A recalibration of the MLLW tidal model for this project would result in the curved line shown in the figure. A hydrodynamic model would fit (calibrate) the induced astronomical tide to the MLLW datums at each gage. The upward shift in the curve from the original model might represent the sea level rise (epoch change) and/or MLW to MLLW conversion.

Of significance is whether this project can be just as effectively modeled using a simple straight-line interpolation between the gauges as opposed to running a full hydrodynamic model. In lower tide ranges, or with dense gauge data, this would be the case. In general, if the estimated variation between a model and straight-line interpolation does not exceed 0.1 ft, then the straight-line interpolation would be acceptable. This variation is indicated by "Δ" in the figure.

Also shown on the figure is the relationship between other geodetic reference datums. The local geoid model (Geoid 03) would provide the undulation shown relative to NAVD88, and indirectly relative to MLLW. As stated previously, this relationship is not critical to maintaining the project on MLLW datum in that RTK observations will be "site-calibrated" to MLLW datum. The figure also illustrates the variation between NGVD29 and NAVD88.

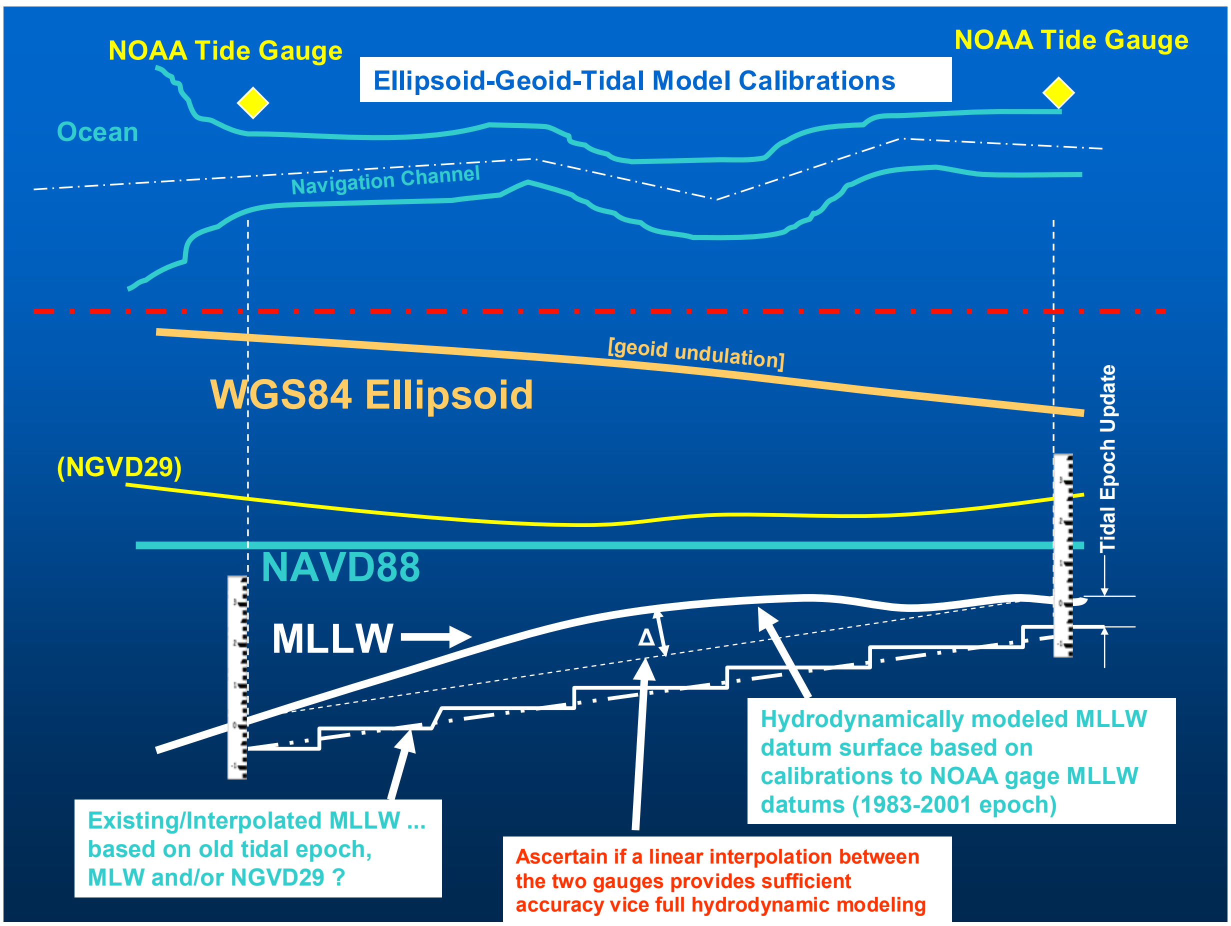

Figure C-13. Tidal Model Calibrations at a Navigation Project

The following figure depicts a navigation project where a simple straight-line interpolation of the tidal datum might be warranted in lieu of performing a full hydrodynamic model study. Initial estimates of changes in time and range of tide for any survey area can be obtained from a review of the NOAA tide prediction "Table 2" information found online. For instance, for the Miami harbor area, go to:

http://tidesandcurrents.noaa.gov/tides07/tab2ec3c.html#91

The tide table values should be used with caution as the data summaries are from observations of varying lengths and various time periods and may be out of date and no longer reflective of current conditions. NOAA will be providing USACE with tables and GIS layers of the latest published tidal and geodetic connection information for all locations which should be used for follow-up.

The tables list mean ranges of tide (MHW – MLW), Spring Ranges of Tide (Range of tide at New and Full moons) and the elevation of Mean Tide Level (MTL) above Chart Datum (MLLW). Data for the Miami area is shown below (in feet).

	Lat	Long	Mn Rge	Spg Rge	MTL
Miami Harbor Entrance	25° 46.1'	80° 07.9'	2.46	2.93	1.39
GOVERNMENT CUT,					
MIAMI HARBOR ENTRANCE	25° 45.8'	80° 07.8'	2.32	2.83	1.32
Biscayne Bay					
San Marino Island	25° 47.6'	80° 09.8'	2.14	2.57	1.21
Miami, Marina	25° 46.7'	80° 11.1'	2.18	2.59	1.22
Dodge Island,					
Fishermans Channel	25° 46.2'	80° 10.1'	2.10	2.52	1.19
Dinner Key Marina	25° 43.6'	80° 14.2'	1.94	2.33	1.10

This project has an adequate density of NOAA tide data and has a relatively small tidal range—around 2.5 ft at the ocean entrance. The mean range of tide varies decreases by 0.16 ft between the Miami Beach Government Cut and inside near the Port of Miami turning basin. Similarly, the 0.14 ft range decrease is small between outside on Miami Beach and Miami Beach Government Cut. The regionally modeled tidal range at a point 3 miles offshore in open ocean could be compared with the range at the Miami Beach pier to see if there is a significant difference. The slope of MLLW can be estimated by looking at the changes in the elevation of MTL relative to MLLW. On the outside, the MTL-MLLW difference is approximately 1.4 ft and decreases to approximate 1.2 ft. inside at the Miami Marina (see Figure C-14 below).

Given the small tide range, and the relatively small tidal range variations between outside and inside, the complexity of the variations is not sufficient to warrant a development of a new hydrodynamic model. Thus, a straight-line interpolation of the model between observation locations would be acceptable. The regional ocean tidal model would be considered in assigning a range value to the model for the outer offshore end of the entrance channel.

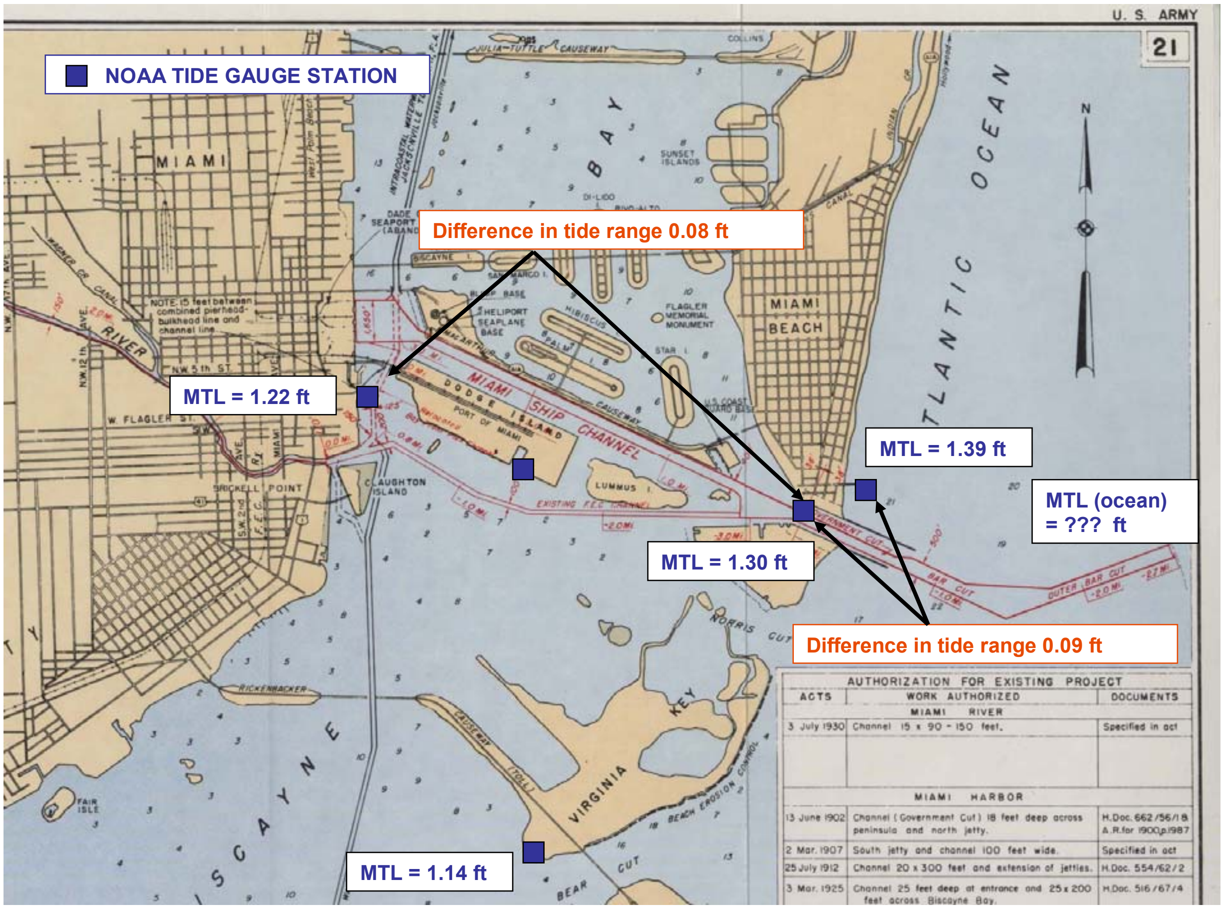

Figure C-14. Tidal Model Calibrations at Miami Harbor

A similar analysis can be made for a West Coast project with a larger tide range—Yaquina River, OR (Portland District). The authorized depth varies from 40-ft at the bar, to 18 ft at Yaquina, then 10-ft to Toledo. The estimate mean range of tide and the MTL-MLLW elevation differences from the tide tables are shown below (in feet).

Yaquina Bay and River	Lat	Long	Mn Rge	Spg Rge	MTL
Bar at entrance	44° 37'	124° 05'	5.9	7.9	4.2
Newport	44° 38'	124° 03'	6.0	8.0	4.3
Southbeach	44° 37.5'	124° 02.6'	6.37	8.34	4.51
Yaquina	44° 36'	124° 01'	6.2	8.2	4.4
Winant	44° 35'	124° 00'	6.3	8.2	4.3
Toledo	44° 37'	123° 56'	6.3	8.1	4.2

However, a check of the latest NOAA tide station published benchmark information shows that the tide table values are out-of-date and should not be used. In general, if the latitude/longitude files have values only to the nearest degree, as opposed to a tenth of a degree, then the data are from pre-1960 observations. Using the latest information collected in the 1980's by CO-OPS, the table becomes (in feet):

	Lat	Lon	Mn Rge	MTL
Bar at entrance	44 37	124 05	5.9	4.2
Newport	44 36.6	124 03.3	6.21	4.49
Southbeach	44 37.5	124 02.6	6.26	4.51
Weiser Point	44 35.6	124 00.5	6.46	4.57
Toledo	44 37.0	123 56.2	6.87	4.71

Thus the older results show much less variability in the tide range than the updated, more recent data. The table and Figure C-15 shows that the range of tide increases by almost 1.0 ft. from outside to upriver at Toledo, and there is a 0.50 ft. slope in MLLW relative to MTL. This may be an area where a hydrodynamic model may prove useful to account for the non-linear changes in the tide going upriver.

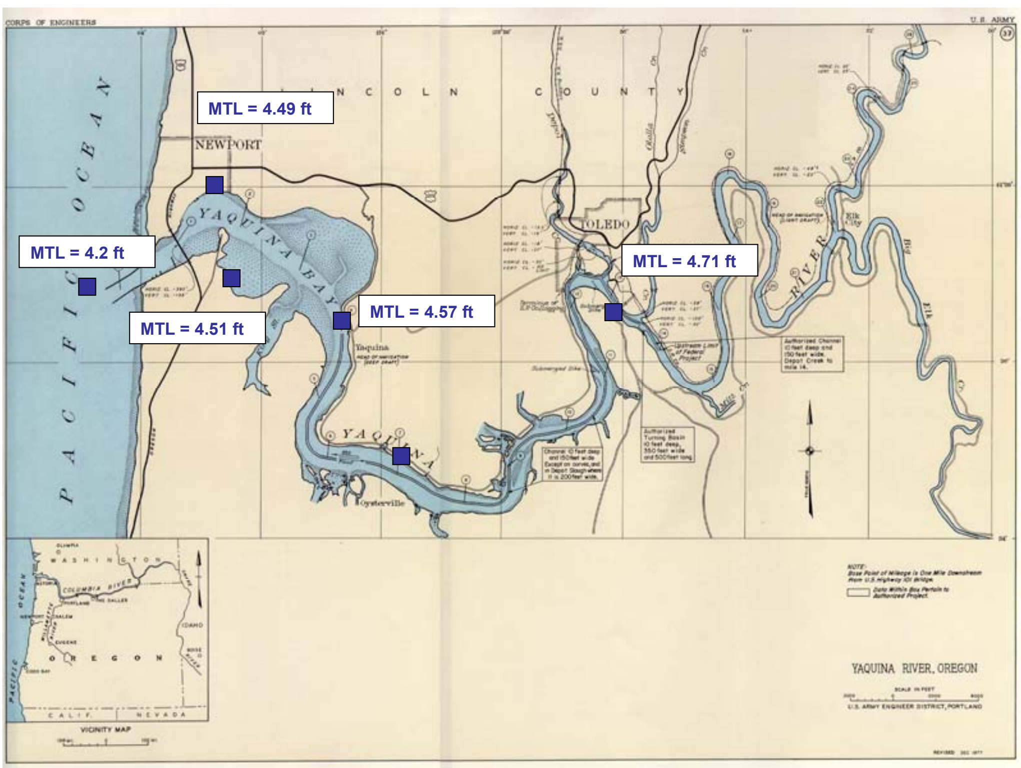

Figure C-15. Tidal Model Calibrations at Yaquina River, OR

The following New England District project (Portsmouth, NH) is typical of a large tidal range variance—approximately 8 ft. MTL variations at various points are shown in Figure C-16.

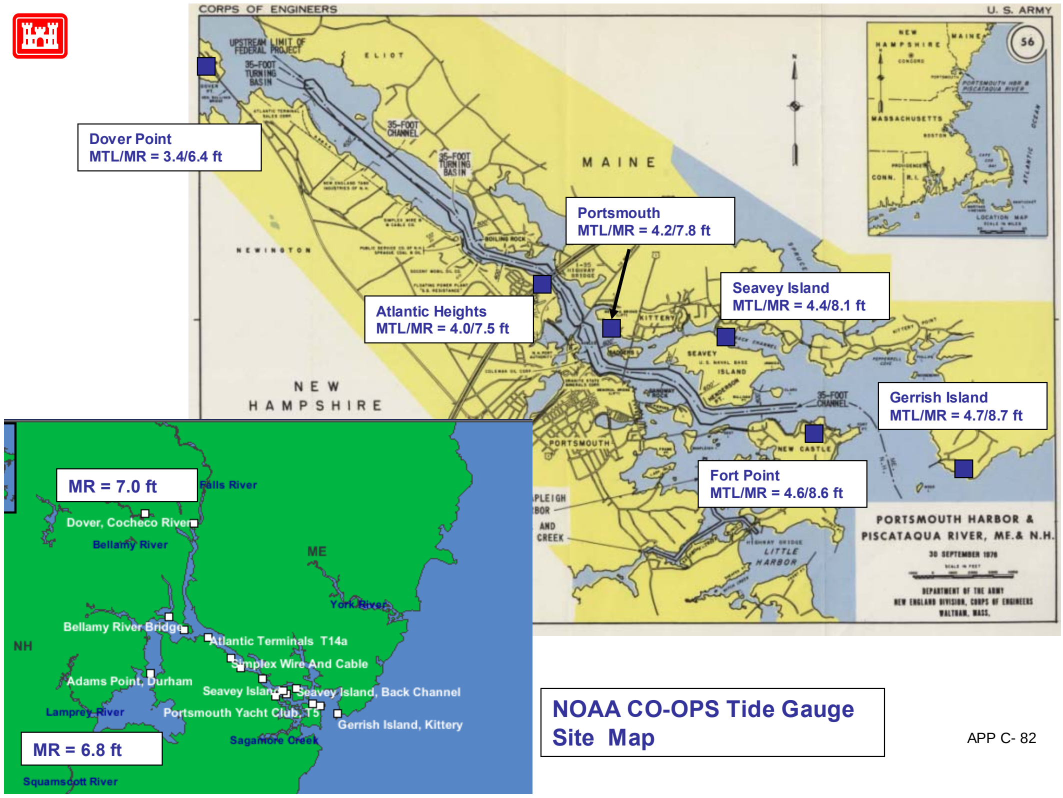

Figure C-16. Tidal Model calibrations at Portsmouth, NH

Portsmouth Harbour	Lat	Long	Mn Rge	Spg Rge	MTL
Jaffrey Point	43° 03.4'	70° 43.9'	8.7	10.0	4.7
Gerrish Island	43° 04.0'	70° 41.7'	8.7	10.0	4.7
Fort Point	43° 04.3'	70° 42.7'	8.6	9.9	4.6
Kittery Point	43° 04.9'	70° 42.2'	8.7	10.0	4.7
Seavey Island	43° 05'	70° 45'	8.1	9.4	4.4
Portsmouth	43° 04.7'	70° 45.1'	7.8	9.0	4.2

Even in these larger tidal ranges the gauge density appears sufficient to adequately model the MLLW datum variation by interpolation throughout the deep draft portion of the project. The following Figure C-17 is a graphic showing the CO-OPS discrete tidal zoning scheme for the project area. If RTK procedures were not employed at this project site, time and range correctors for each zone would be applied to an appropriate tide station installed in the harbor to account for time and range changes in the project area. The closest NOAA operating NWLON stations are Boston, MA and Portland, ME.

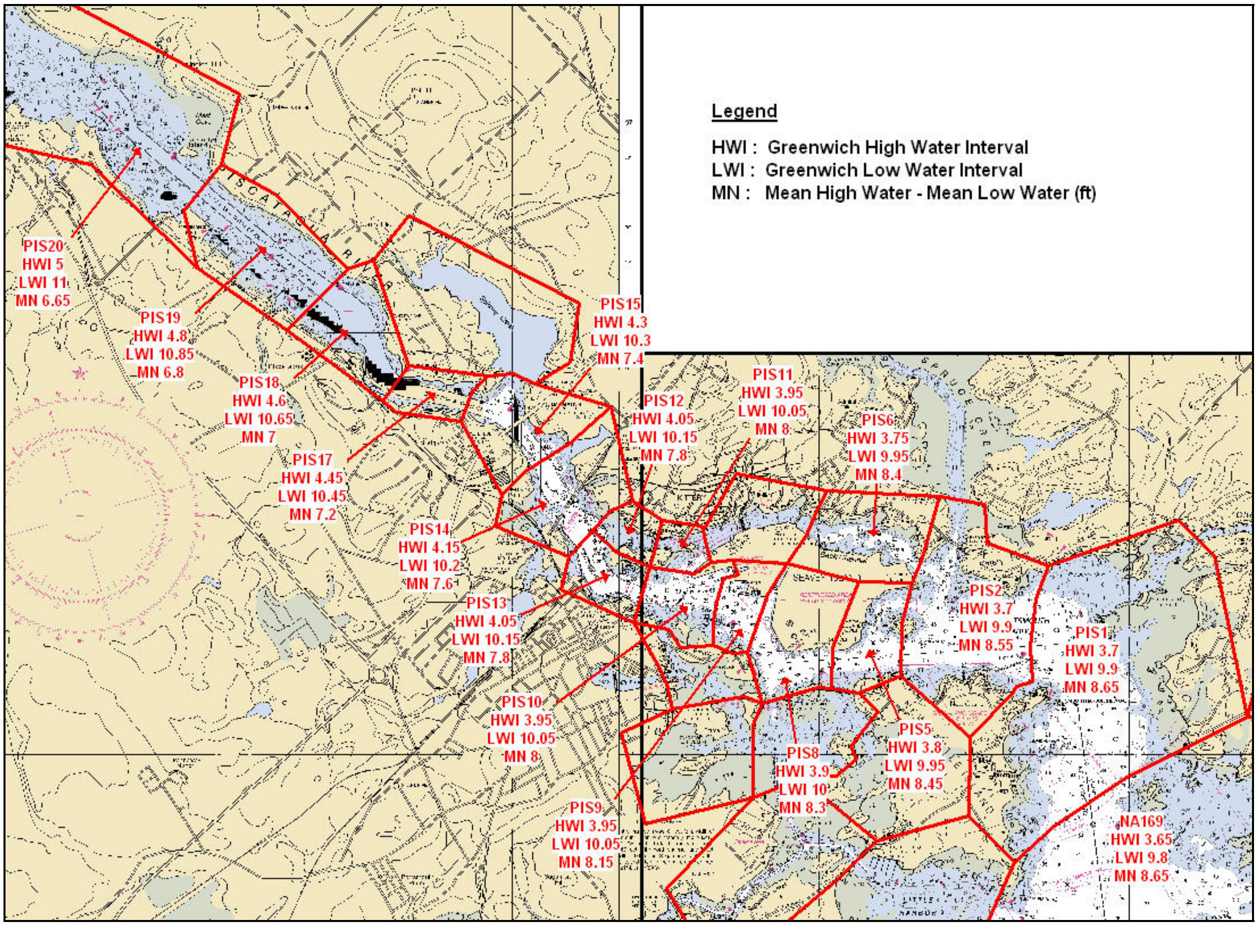

Figure C-17. NOAA Discrete Tidal Zoning Scheme for Portsmouth, New Hampshire

C-16. Hydrodynamic Tidal Modeling of Navigation Projects

From the above, it would appear that many deep-draft navigations will have a sufficient density of NOAA CO-OPS tidal data that interpolation models will be adequate. Interpolation models can be:

- a linear interpolation of elevation relationships over relatively short distances
- a discrete tidal zoning interpolation based on changes in cotidal lines over the survey area
- a continuous tidal zoning interpolation model such as TCARI

Where this is not the case, then a hydrodynamic tidal model may have to be generated to define the MLLW datum plane throughout a project.

The technical process of developing a hydrodynamic tidal model of a typical coastal inlet, and calibrating that model to one or more fixed gauges, is relatively straightforward and models for performing this are well documented in the USACE Coastal Engineering Manual (EM 1110-2-1100—Part II-5 and Part II-6) and other sources. Many USACE navigation projects have been extensively studied over the years and existing numerical models may be readily utilized to assess the tidal datum relationships—e.g., activities studied under the ERDC/CHL Diagnostic Modeling System.

Projects requiring hydrodynamic tidal modeling to define the MLLW datum can be accomplished by any number of organizations. Some of these include:

- District Hydrology & Hydraulics (H&H) section
- Coastal Engineering A-E firms
- NOAA (Office of Coast Survey—VDatum Group)
- ERDC/Coastal Hydraulics Laboratory (CHL)

Each of the above will have different approaches, costs, and turn-around response. CEPD cost estimates for this modeling effort can be obtained from any of these organizations. These costs may include gauging programs which will have to be obtained from NOAA. Actual installation can be accomplished via an A-E contract with a coastal engineering firm.

It is recommended that those performing the CEPD assessment closely coordinate with the H&H team in your District. Working with them will best develop the requirements, estimated costs, and implementation plan.

C-17. National VDatum

VDatum, coupled with the Tidal Constituent and Residual Interpolation (TCARI) continuous tidal zoning model, has considerable future application to many USACE projects—both inland and coastal. VDatum is a software tool developed by NOAA that allows users to transform geospatial data among a variety of geoidal, ellipsoidal, and tidal vertical datums. Currently the software is designed to convert between 28 vertical datums, including NAVD88 and MLLW. This is important to coastal applications that rely on vertical accuracy in bathymetric, topographic, and coastline data sets, many of which may be produced on different reference datums but need to be merged for hydrodynamic surge models. The VDatum software can be applied to a single point location or to a batch data file. Applying VDatum to an entire data set can be particularly useful when merging multiple data sources together, where they must first all be referenced to a common vertical datum. Emerging technologies, such as LIDAR and kinematic GPS data collection, can also benefit from VDatum in providing new approaches for efficiently processing shoreline and bathymetric data with accurate vertical referencing. Given the numerous applications that can benefit from having a vertical datum transformation tool, the NOAA goal is to develop a seamless nationwide VDatum utility that would facilitate more effective sharing of vertical data and also complement a vision of linking such data through national databases (Myers 2005). See also NRC 2004.

A VDatum model is generated using hydrodynamic modeling tools as shown in Figure C-18.

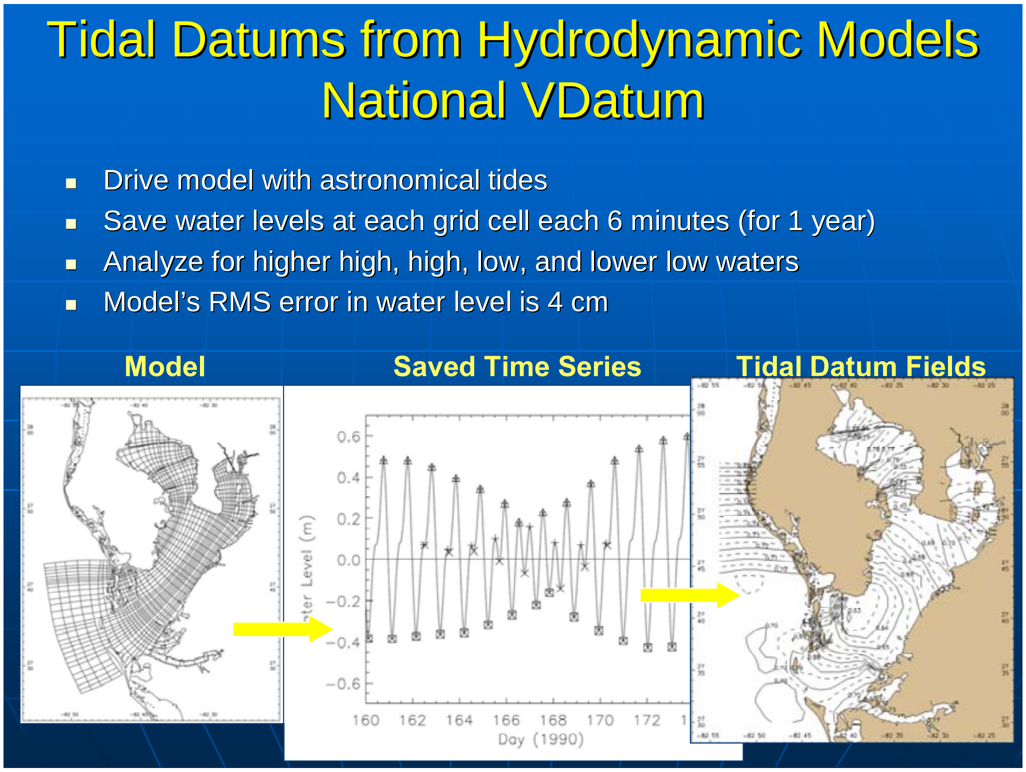

Figure C-18. NOAA National VDatum

The CEPD evaluation should check with NOAA to assess if VDatum coverage over a particular navigation project is adequate for direct generation of a MLLW tidal model of a navigation project passing through the NOAA model. This would entail evaluating the sensitivity, resolution, and density of the VDatum model.

C-18. NOAA Requirements for Short-Term Tide Gauges Needed to Update Tidal Models at a Navigation Project

When historical NOAA tide gauge sites are occupied, or additional gauging data is needed to model the tidal regime at a navigation project, NOAA requires the following minimum standards in order for the site to be included in the CO-OPS NWLP database.

- Types of recording gauge. At a new site, any temporary gauge that can measure record water levels at 6-minute intervals is suitable. The gauge must be firmly tied in and referenced to the local tidal benchmarks at the site.

- Location of temporary gauge. To be specified by modeler or NOAA CO-OPS.

- Length of record. Minimum of 30 days. Longer term if required by NOAA CO-OPS. (A shorter term—3 to 7 days—may be used for calibrating hydrodynamic models)

- Tidal Benchmarks. Five (5) benchmarks are required around the gauge site. Follow mark construction requirements in Appendix B. (No deep driven rods are required).

- Data format and submittal. Follow NOAA CO-OPS submittal requirements.

- Datum transfer computations. Follow NOAA CO-OPS standards—NOS 2003. NOAA CO-OPS will check datum transfer computations if they are performed in-house or by an A-E.

- 3rd Order leveling between tidal benchmarks. Follow standard procedures in EM 1110-1-1005 for both new and existing gauge sites.

- Primary tidal benchmark elevation. Tidal benchmarks at both new and existing sites will be referenced to and input to the NSRS (NAVD88) using CORS-Only/OPUS & OPUS DB input methods outlined in Appendix B—i.e., ±0.25 ft accuracy.

C-19. Connecting Tide Gauge Reference Benchmarks to the NSRS (NAVD88)

It is desirable, but not absolutely essential, for USACE navigation project dredging and surveying applications, to reference MLLW datums at tidal benchmarks to NAVD88. Since navigation projects are referenced exclusively to MLLW, geodetic datums do not enter into the datum reduction equation other than initially referencing RTK ellipsoidal measurements. However, these ellipsoidal measurements are always recalibrated to local MLLW; therefore the geodetic relationship need only be estimated.

In order to support NOAA's program to update tidal benchmarks to NAVD88 (and the NSRS) for National VDatum densification, NOAA tidal benchmarks will be positioned using the CORS-Only/OPUS ±0.25 ft (±8 cm) methods described in Appendix B. These elevation observations will be input into the NSRS using the OPUS DB procedures also referenced in Appendix B. This support effort would occur only at new tidal benchmarks in USACE projects being updated to the latest MLLW model, and only at tidal stations used to calibrate a tidal model of the project.

NSRS benchmark descriptions for these tidal marks will follow the same guidance in Appendix B for river gauges; namely, record elevation differences between gauge reference marks and nearby benchmarks in NSRS station descriptions and periodic recovery notes.

Recovery notes on CO-OPS tidal benchmarks not published in the NSRS (but published in the NWLN database without a PID link) will be transmitted directly to CO-OPS.

C-20. Interim Options Pending RTK Implementation and Tidal Modeling

Districts with projects not on a NOAA certified MLLW datum should endeavor to minimize navigation project elevation errors by considering some of the following steps pending updates:

- Use NOAA tide gauge benchmarks for reference or run levels or static GPS to transfer NOAA MLLW (epoch 1983-2001) elevations to a more suitable benchmark

- Evaluate existing tidal models for reasonability

- Attempt to minimize the extrapolated distance between the gauge/staff and the project site

- Perform linear interpolation between gauges if multiple gauges are available

- Develop an interpolation model (tidal zoning or TCARI) for project (range and time corrections)—contact NOAA VDatum Group or CO-OPS as these may already exist

- Reevaluate any estimated tidal datums in offshore entrance channels based on newer ocean models

- Develop a preliminary (estimated) tidal-geoid model for project—KTD file

- Implement use of RTK survey methods as soon as possible

In some areas (large open bays), RTK observations may be beyond the range of this measurement method. Alternative methods (e.g., VRS networks) are available to extend the range of RTK systems, as is being done by Philadelphia District in Delaware Bay.

C-21. Coastal Hurricane and Shore Protection Projects (HSPP)

Coastal hurricane protection and shore protection structures include levees, breakwaters, floodwalls, revetments, jetties, groins, and dikes. Beach restoration projects are also included in this category. Hard structures are usually designed and constructed relative to a local tidal datum, such as MSL, MLW, MLLW, or MHW. For example, the San Pedro breakwater shown in Figure C-19 has elevations relative to MLLW datum.

The CEPD assessment of these projects is intended to verify (1) that the design/constructed sea level reference datum is current (i.e., latest tidal epoch and model) and (2) that the local project control has been connected with the NSRS (NAVD88).

Many shore protection projects have been designed to sea level datums based on interpolated or extrapolated references from gauges. Depending on the type of gauge, tidal range, and the distance from the gauge, this interpolation or extrapolation may be valid, or sufficiently accurate—say within ±0.25 ft of the reference water level datum. Obviously, with sea level rise, the crest elevation of structures may be below that originally designed. However, the original design documents should be checked to verify that allowance for sea level rise was considered in the design elevation.

Connection to the NSRS need only be at the ±0.25 ft accuracy level, as was the case with inland flood control projects. This connection is simply to provide other using agencies with an elevation on a federally recognized reference system—NAVD88.

Evaluated shore protection projects that are not on updated tidal and/or NSRS datums will require additional effort. In general, the updated sea level datum can be estimated (interpolated) given sufficient NOAA or Corps gauges exist in the region. The NSRS connection will normally be performed following the same accuracy standards and field survey specifications used for flood control structures in Appendix B—e.g., ±0.25 ft accuracy CORS-Only/OPUS and OPUS DB methods. At least one primary benchmark on each project shall have both a water level reference elevation and a NAVD88 elevation.

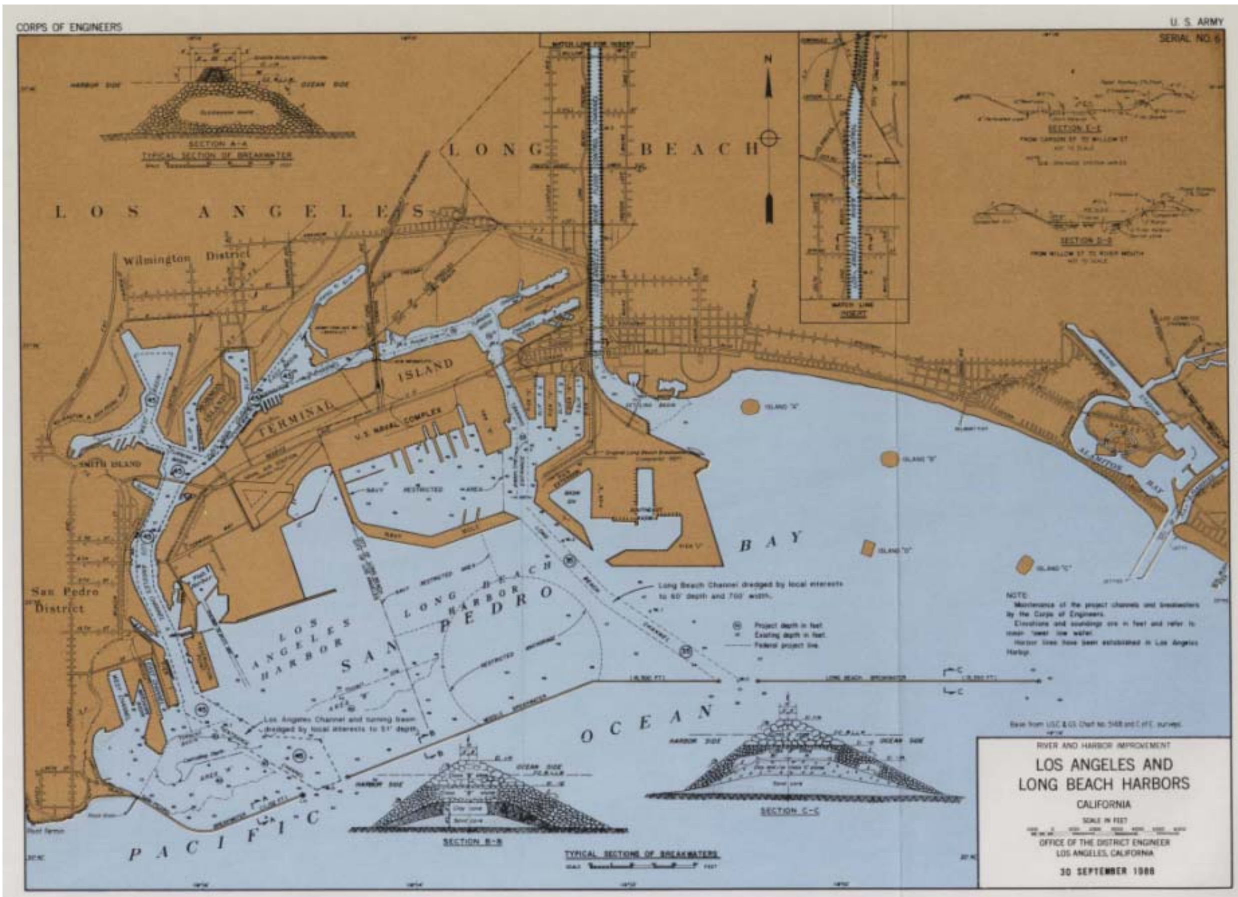

Figure C-19. Shore protection breakwaters—Los Angeles & Long Beach Harbors

C-22. Beach Renourishment/Restoration Projects

Beach restoration projects are usually designed relative to either tidal or geodetic datums, depending on local preferences. More often than not, this relationship between geodetic and tidal datums is not firmly established. As with the shore protection projects above, the reference benchmarks should be related to the latest tidal datum and have a firm reference to the NSRS (NAVD88).

The reference tidal datum may have been estimated from nearby gauges. In Figure C-20 below, gauges may or may not have been used to determine the reference datum at each of the projects on Staten Island. Interpolations between more distant gauges may have been used. Such an interpolated "model" is normally of sufficient accuracy—and normally would not exceed ±0.25 ft. The NAVD88 elevation on the primary benchmark at each project can be determined by CORS-Only/OPUS observations. As in flood control projects (Appendix B) this NAVD88 elevation would not supersede local project control relative elevation differences. However, the other marks may be adjusted to NAVD88 using the most recent leveling or RTK observations made between the marks.

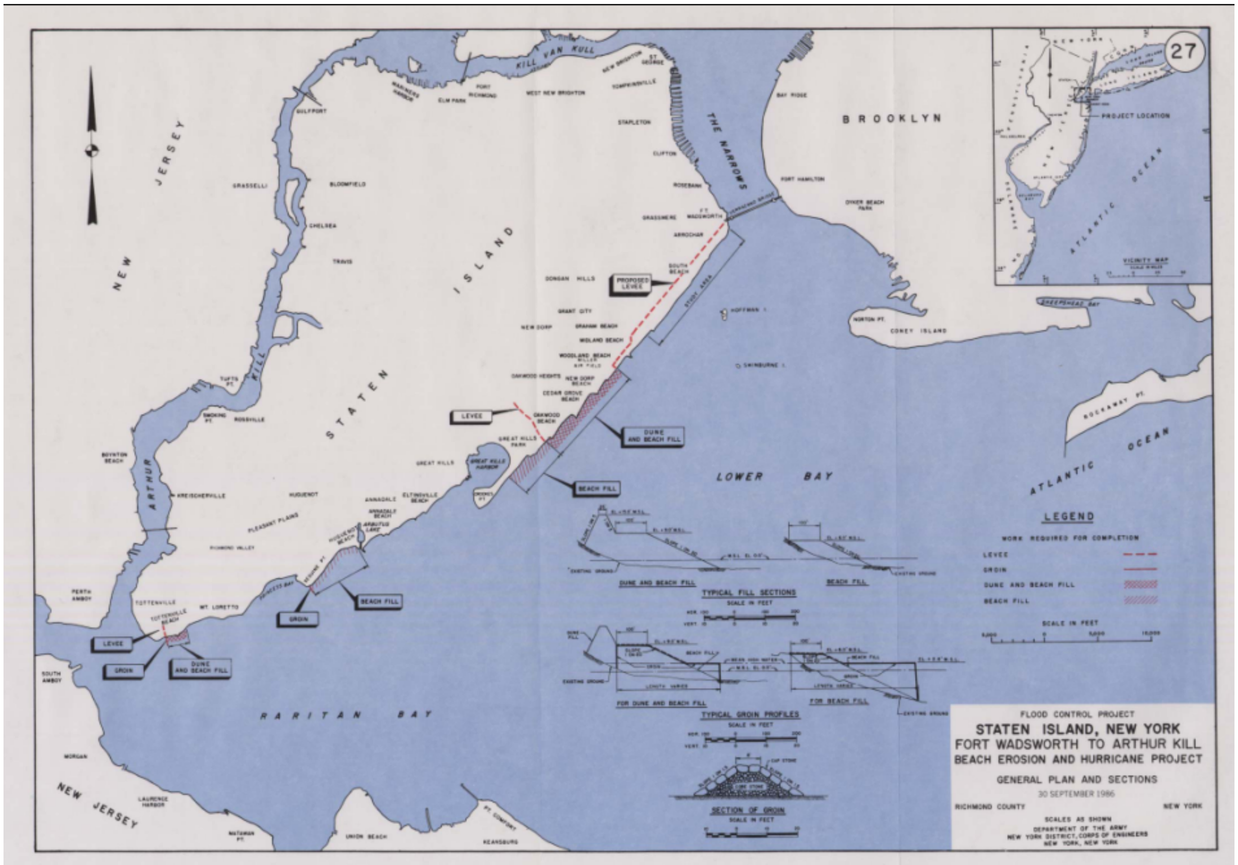

Figure C-20. Beach Erosion & Hurricane Protection Projects—Staten Island, NY

Beach renourishment/restoration projects are typically constructed relative to pre-set range monuments. On many projects, these fixed reference monuments are based on “NGVD,” NGVD29,” “MSL,” or perhaps “NAVD88.” In Figure C-21 below, taken from construction plans, the “NGVD” elevation of the range monument “PROFILE R-74.743” was likely determined in 1974 when the range monument was set. The original or current relationship with the NSRS is probably unknown. Its “NGVD” relationship to MLW (-1.0 ft) or MHW (+1.1 ft) is likely based on the relationship at the nearest NOAA tide gauge, which may be some 10 to 30 miles distant. The tidal epoch must be also indicated—in the above project, a quarter-foot tidal epoch difference may be indicated given the NGVD-MLW references. In this case, the entire beach project would be constructed 0.25 ft below the intended (design) elevation.

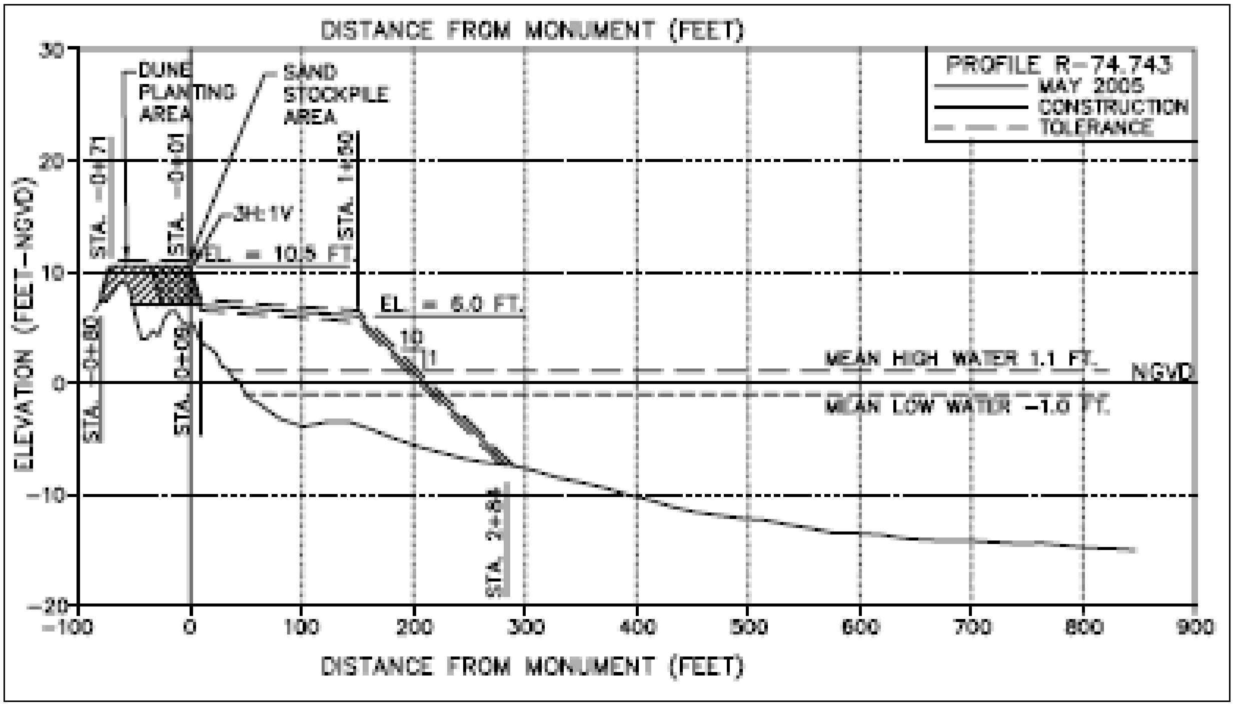

Figure C-21. Beach Renourishment Project—Typical Section

Evaluated beach erosion and hurricane protection projects that are not on updated tidal and/or NSRS datums may require additional effort. In general, the updated sea level datum can be estimated (interpolated) given sufficient NOAA or Corps gauges exist in the region (assuming no gauge data exists for the actual project location. An interpolated tidal range between two NOAA gauges would be reasonable if the tidal ranges at each gauge do not vary significantly—say < 0.3 ft. Once NOAA completes VDatum coverage for the entire US coastal areas, then a more refined (modeled) datum can be updated.

The NSRS connection will normally be performed following the same accuracy standards and field survey specifications used for flood control structures in Appendix B—e.g., ±0.25 ft accuracy CORS-Only/OPUS and OPUS DB methods. Only one primary benchmark on a beach renourishment project need be connected with the NSRS, assuming the relative elevations of other local project control benchmarks are firmly related to the primary mark.

Offshore borrow area elevations (or depths) may also be defined relative to different datums—MLLW, MSL, NGVD29, or NAVD88. Even beach profiles can have different datums and reference points on the same line—the shoreward section may be relative to a fixed range monument and the offshore portion may be relative to a sea level reference at a distant gauge. CEPD efforts must ensure that all measurements in a project stem from a common reference system and framework—i.e., benchmarks on the NSRS with consistent geodetic and sea level relationships.

C-23. Navigation Projects on the Great Lakes and Connecting Waterways

Navigation and shore protection projects on the Great Lakes and connecting waterways are normally referenced to the latest International Great Lakes Datum (IGLD). IGLD is specified by a year of the adjustment (IGLD 1955 superceded by IGLD 1985) Each lake has its own separate reference to IGLD 1985 defined by a NOAA nautical chart reference datum called Low Water Datum (LWD) as follows:

Heights of Low Water Datum (LWD) relative to IGLD 1985

Waterway	Feet	Meters
Lake Ontario	243.3	74.2
Lake Erie	569.2	173.5
Lake St. Clair	572.3	174.4
Lake Huron	577.5	176.0
Lake Michigan	577.5	176.0
Lake Superior	601.1	183.2

The datum reference in the connecting channels slopes between the fixed datums at each lake. The following Figure C-22 notes the reference elevations are based on the IGLD 1955, which has been superseded. References to current and superseded datums need to be assessed during the CEPD process.

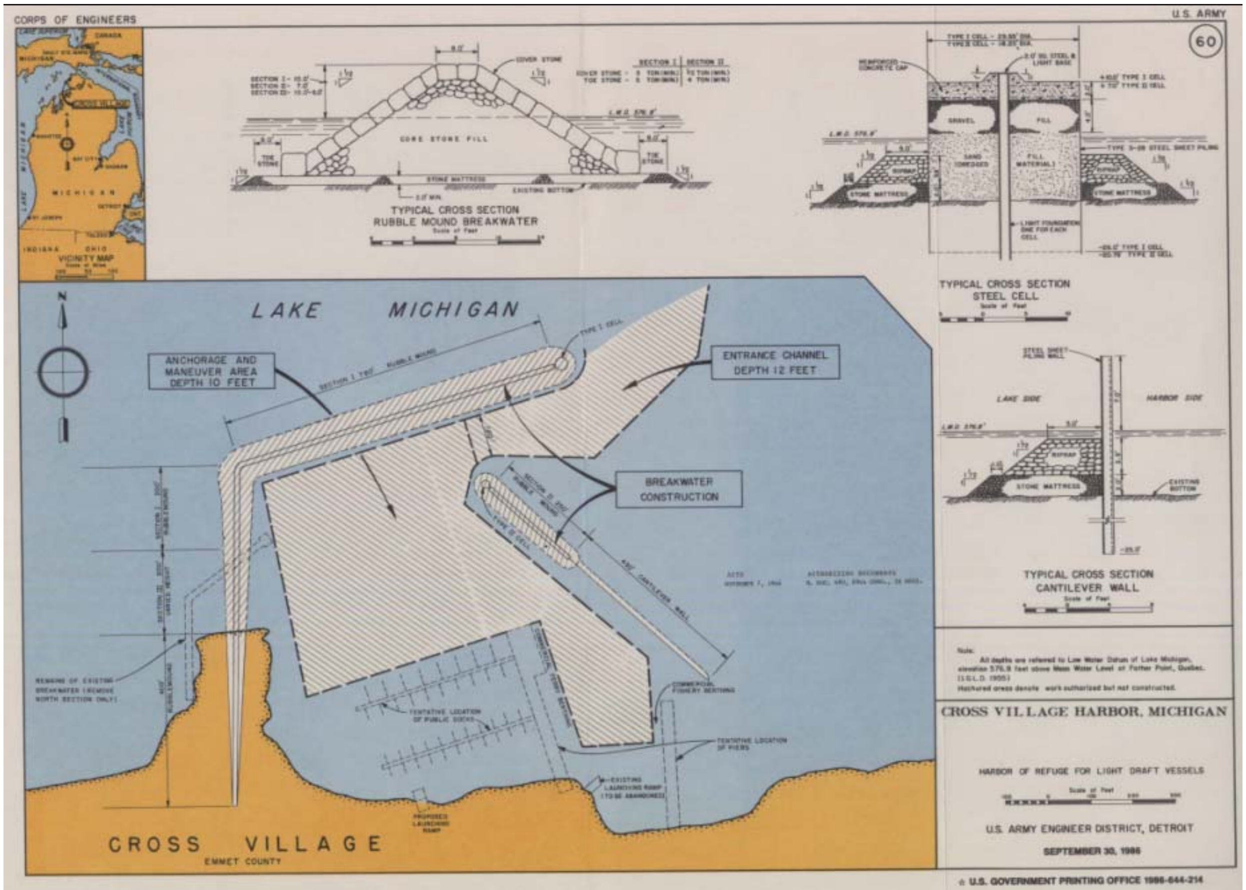

Figure C-22. Great Lakes IGLD55 reference

Primary project control benchmark connections to the NSRS would follow similar guidance outlined for flood control projects in Appendix B. In Figure C-23, elevations up the Fox River are referenced to a reference elevation at Green Bay, WI, which in turn is based on IGLD55. Low water pool elevations between the locks are not indicated on this drawing; however, they may be shown in the detailed design or as-built documents. Periodic connections to the NSRS at primary control benchmarks along this project would be beneficial. This reference would only need to be made to the ±0.25 ft accuracy level using CORS-Only/OPUS and OPUS DB methods.

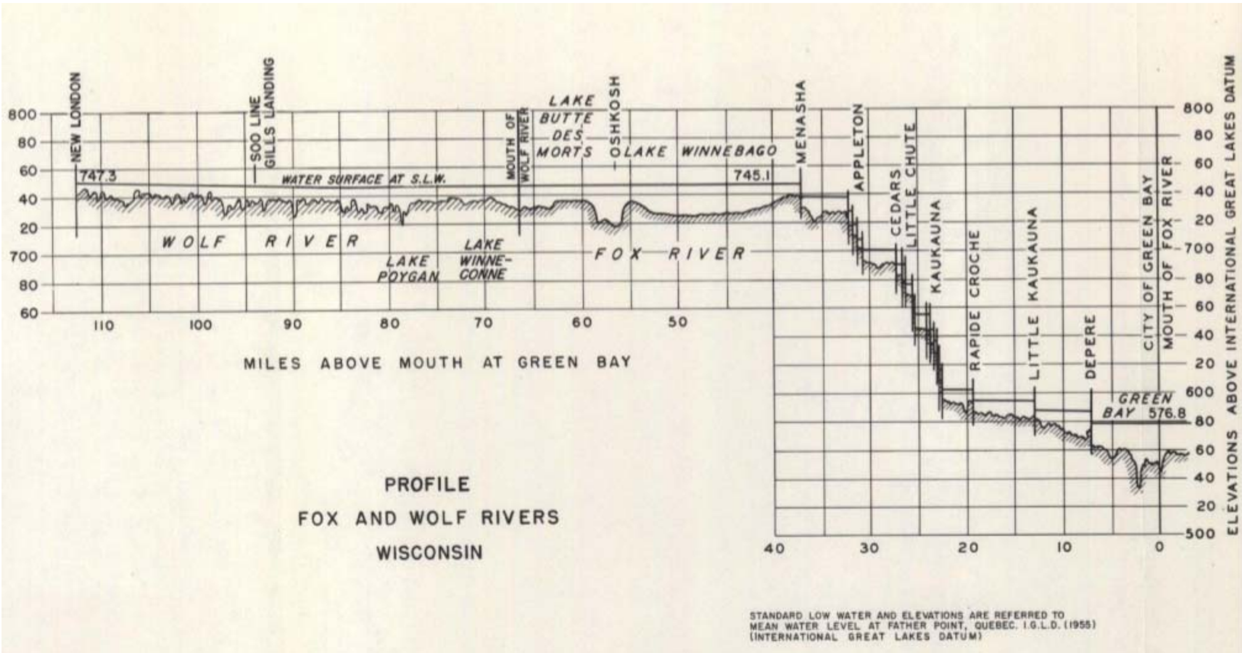

Figure C-23. IGLD55 reference on Fox River, WI

Note also that IGLD85 elevations are referenced to dynamic heights which differ from NAVD88 Helmert orthometric heights, as summarized below.

- NGVD29 -- “Normal” Orthometric Heights
- NAVD88 -- Helmert Orthometric Height
- IGLD85 -- Dynamic Height

Dynamic Heights are not equal to Orthometric Heights. Orthometric heights are distances from a reference surface normal to equipotential surfaces; however, they do not represent an equipotential surface. Dynamic heights define geopotential surfaces and represent distances based on hydraulic head differences (ie, work); thus, they may have significant application in Corps projects where head differences are critical—not only in the Great lakes but also on rivers or canal systems. The dynamic height of a benchmark is the height at a reference latitude of the geopotential surface through the benchmark. This value is of interest because two stations with different orthometric heights may have similar geopotential, due to undulations of the geopotential reference surface (geoid). The source of a dynamic height is always computed. The reference latitude for the US is North 45 degrees. The dynamic height is computed from a geopotential height. The geopotential height (a.k.a. geopotential number) is determined by:

$$\text{Geopotential Height } C = \text{Orthometric Height} \cdot (\text{Gravity} + (4.24E^{-5} \cdot \text{Orthometric Height}))$$

A dynamic height is then obtained by dividing the adjusted NAVD88 geopotential height (C) of a benchmark by the normal gravity value (G) computed on the GRS 80 ellipsoid at 45 degrees latitude (G = 980.6199 gal).

$$\text{Dynamic Height} = C/G = \text{Geopotential Height}_{\text{NAVD88}} / \text{Normal Gravity}_{\text{GRS80 } 45^{\circ}}$$

Measured elevation differences between benchmarks do not yield either orthometric height differences or dynamic height differences. Spirit level differences in elevation must be corrected (Orthometric Correction or Dynamic Correction) to obtain an orthometric heights or dynamic heights. See Meyer 2006 (Part III) and IJC 1995 for additional details on the differences between orthometric and dynamic datums.

Due to inaccuracies in NAVD88 leveling adjustments, a "hydraulic corrector" must be applied at subordinate points on the Great Lakes in order to obtain a reference engineering, construction or navigation datum. These hydraulic correctors are published by the IJC Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data. An example of this correction is shown below:

Lakeport MI BM Burtch dynamic elev	178.796 m
LWD ref datum (Harbor Beach)	176.000
LWD water surface (Har Bch) below BM	2.796
Hydraulic Corrector	- (+ 0.202)
Local LWD reference water surface below BM Burtch (IGLD85)	2.594 m

- A staff gage would be set with "zero" set 2.594 m below BM Burtch
- This represents the construction reference datum for this project area
- Hydraulic corrector not available at all projects … must interpolate
- No hydraulic corrector is applied in connecting channels
- Accurate vertical datums are critical to channel condition reports used by commercial shippers loading iron ore 4 to 6 inches above rock-cut channels

C-24. Prioritizing Evaluation of Deep- and Shallow-Draft Navigation Projects

With over 900 navigation projects—approximately 299 deep draft and 627 shallow draft—the CEPD level of effort will have to be prioritized. The first step would be to separate out deep draft projects (>15 ft) from the lower priority shallow draft projects. The deep draft projects should be evaluated first, and in a prioritized order considering tonnage, bottom type, maintenance dredging frequency, average cost per CY, disposal costs, etc. These same criteria might be used in scheduling any corrective update actions needed

Many shallow draft projects will not economically warrant extensive CEPD evaluation or subsequent updating actions. This would be the case in projects with minimal maintenance that are primarily small recreational or fishing projects with little traffic—typically those projects in the 4 to 8 ft depth range. Some of these projects may be on an "assumed" tidal datum, or are referenced to a local benchmark on NGVD29 whose elevation is of uncertain origin and is not published in the NSRS database.

It is difficult to estimate the level of effort that should be expended in updating reference datums on these low-maintenance shallow draft projects. The main factor in prioritizing these projects would be long-term construction and maintenance costs on a project. Other factors like traffic and types of vessels might be used. Thus, a 4-ft draft project used primarily for shallow-draft recreation (e.g., Jet skies, canoes) will be at the bottom of the priority list, and only a cursory evaluation and update would be warranted.

Shallow draft project tidal ranges may also be estimated using either local gauge data or interpolated between nearby gauges. At minimum, the project reference should be updated to the latest NOAA tidal epoch even if the tidal range is estimated based on adjacent gauges. If the project has no gauge history, it is problematic whether an older "reference" benchmark on NGVD29 is a reliable datum reference. Likewise, a CORPSCON/VERTCON datum conversion to NAVD88 may also not be reliable if the two datums are not sufficiently modeled in this area. Connecting this benchmark with NAVD88 at another gauge site would be recommended. However, for many low priority shallow draft projects, there would be no urgency in performing this geodetic connection—it could be scheduled the next time a routine Project Condition Survey is performed.

In time, NOAA VDatum hydrodynamic coastal models may provide updated tidal and geodetic models for these isolated projects. Thus, deferring corrective actions (i.e., field surveys) on many low priority projects may be the recommended course of action. Deferring field surveys does not imply that the tidal epoch and model is not evaluated and updated.

C-25. CEPD Assessment of Navigation Project Models

Each navigation project being evaluated under the CEPD should be reviewed in the order below.

- Prioritize deep- and shallow-draft projects

- Obtain project documents from various District technical elements—control data, original design memorandums, recent maintenance plans & specs, current tidal datum and models, etc.

- Obtain VDatum coverage, gauge, and tidal benchmark records from NOAA CO-OPS.

- Estimate requirements. Project is on correct water level and geodetic datums, or will updated tidal modeling and field survey work be required.

- Recommended corrective action if additional work is required.

- Budget estimate. Prepare program budget time and cost estimate to update or correct project datum.

- Project Report. Draft project report and web-based report for each project, to include estimated program year and cost—see Appendix D.

- Implementation. Perform recommended corrective actions in programmed out year.

For deficient projects requiring additional gauging and/or hydrodynamic tidal modeling, the actual implementation action may require an assessment of the items in the following checklist. Not all of these steps will be applicable to every project.

Pre-Assessment Phase

- Obtain project limits
- USACE project requirements
    - Maintenance dredging frequency
    - Costs
    - Survey methods (RTK or direct gauge)
- Obtain next USACE maintenance dredging schedule
- Review original design memorandums and congressional authorizations
- NSRS Information
    - Distance from CORS stations
    - Geoid model accuracy
    - NSRS benchmark locations
- Tidal Information from CO-OPS
    - NWLON station locations
    - PORTS locations
    - Historical tide stations
    - NAVD88 connections at tidal benchmarks
    - GPS connections to tidal benchmarks
    - Local sea level trends
    - Cotidal charts
    - Tidal Zoning charts
    - VDatum availability—existing or planned
- Availability of existing models (in-house, A-E, ERDC, NOAA)

Assessment Phase

- Tides
    - Knowledge of tidal characteristics
    - Gaps in NWLON coverage
    - Gaps in published tidal datums
    - Gaps in stations with harmonic constants
    - Gaps in geodetic datum and GPS connections
- Geodesy
    - Gaps in NSRS coverage
    - CORS coverage (within 200 miles)
    - Lack of GPS surveys
    - Geoid accuracy assessment
- VDatum Assessment
    - Need to enhance existing VDatum, if one exists
    - Assess need for VDatum approach vice:
        - Project size & spatial changes in tidal characteristics
        - Changes in relationships of LMSL vs. geodetic datum

Operations Requirements Planning Phase

- Determine requirements for additional tidal datums and harmonic constants
- Determine requirements for new geodetic datum/GPS connections to tide stations
- Determine requirements for new CORS at a tide station
- Determine requirements for enhanced NSRS benchmarks

- Determine VDatum requirements
- Determine requirements for operation of tide stations during dredging and hydrographic survey operations
- Determine need for discrete tidal zoning, TCARI, VDatum, or use of RTK with VDatum for dredge or survey vessel elevation control.

C-26. Example of a CEPD Budget Estimate for Updating a Navigation Project

The following example is representative of a "worst case" project condition used to exemplify the various cost items that might be needed in updating the datum at a project. This hypothetical case assumes that a deep-draft project is on an uncertain pre 1960-1978 tidal epoch, that there has never been a NOAA tidal gauge or Corps gauge at the project, and there is no published NSRS vertical control around the project. The project has been maintained relative to a Corps benchmark of uncertain datum—both geodetic and tidal. A large tidal range variation is known to exist between the entrance and inland port facility—thus, a hydrodynamic model will be required. (Note that these "worst case" conditions will rarely occur on USACE deep draft projects. Most projects will have historical gauge data, NSRS vertical control, and/or an adequate density of tidal model data such that hydrodynamic modeling is not required)

To prepare a CEPD budget estimate for developing a MLLW reference datum at this navigation project, the following actions need to be considered.

- Set temporary gage for 30 days following NOAA CO-OPS requirements
- Set 5 tidal benchmarks at temporary gage site
- Connect one primary tidal benchmark to the NSRS (via CORS-Only/OPUS)
- Input NSRS connection and tidal benchmark descriptions to NSRS (OPUS DB)
- Run levels between tidal benchmarks and temporary gage (furnish direct to CO-OPS)
- Compute tidal datum transfer from NWLON gauge to temporary gauge (CO-OPS action)
- Develop and calibrate hydrodynamic tidal for project (In-house, CO-OPS, A-E)
- Develop tidal-geoid model for project
- Update project files

A cost estimate will follow the same format and simulated rates as the estimate in Appendix B.

<u>Contract Administration</u>

USACE hired-labor, technical S&A, coordination with NOAA, A-E, in-house (Project Manager)	30 MD @ $800/MD	$24000
USACE hired-labor, technical (H&H, Engineering, etc)	30 MD @ $800/MD	$24000
USACE hired-labor, CT admin charges		$7500
USACE hired labor & travel (site recon) (Proj Mgr)	5 MD @ $800/MD	$4000
	Travel	$1000
	TOTAL	$60500

A-E Contract Line Items

Set Temporary Tide Gauge

Mob/demob to project site [CD]	2 CD @ $2500	$5000
Construct/install temporary gauge	1 CD @ $2500	$2500
Gauge rental	30 d @ $100/d	$3000
Set/level/describe 5 tidal benchmarks	1 CD @ $2500	$2500
Record, process, transmit data to NOAA	5 MD @ $800	$4000
A-E Project Manager S&I	5 MD @ $1500	$7500
	TOTAL	$24500

Connect Primary Tidal Benchmark to NSRS/NAVD88

Recon for existing NSRS or USACE control	1 CD @ $2500	$2500
GPS, static baseline observations CORS	1 CD @ $2500	$2500
Process data (OPUS), transmit to NGS/CO-OPS	2 MD @ $800	$1600
	TOTAL	$6600

Data Processing and Reporting

NOAA CO-OPS: Process 30 day datum transfer, update database $5000 est

Develop/run hydrodynamic tidal model (In-House, A-E, NOAA, ERDC/CHL)
- Obtain topographic data for model
- Obtain/generate bathymetric data for model
- Obtain 30 d tidal data results from NOAA
- Run, calibrate & analyze model—develop tidal model
- Develop MLLW-geoid file for project

Total modeling costs: $10000 to $50000 est

USACE or A-E hired-labor to update documents & files	5 MD @ $800	$4000
	TOTAL	$19000 to $59000

Summary

Contract Administration	$60500
A-E Contract Line Items	$24500
	$ 6600

Data Processing and Reporting	$19000 to $59000
Subtotal	$110600 to 150600
Contingencies @ 10%	$ 11060 to $15060
TOTAL BUDGET ESTIMATE	**$121000 to $165000**

Obviously the largest (and most uncertain) line item is the tidal modeling. This cost will largely depend on the ready availability of topo/bathy models. If these models have to be created, the cost will significantly increase. The agency performing the model will also impact the cost. The high $50K estimate may represent only 40 hours labor.

If an additional temporary gage is needed to better calibrate the tidal model, then the $30K field cost would roughly double.

In developing a program estimate, the Project Manager should closely coordinate the project requirements with H&H to insure that reasonable budget estimates are obtained—especially if any hydrodynamic modeling is required.

Using this same project with a more "typical" Corps scenario will yield a significantly reduced budget estimate. A more typical Corps deep-draft project condition being evaluated might include the following findings.

- Two or more historical NOAA gauges exist within the project, and these gauges have been updated to the latest epoch; thus, the tidal datum can be adequately modeled by linear interpolation.
- One of the NOAA gauge tidal benchmarks is published on the NSRS and includes an adjusted NAVD88 elevation.
- The Corps reference benchmark being used on the project is on NGVD29. However the benchmark is only a mile from the NOAA tidal benchmark on NSRS.
- The existing MLLW datum model for the project is of unknown origin or accuracy.

Basically, the CEPD assessment requirements for the project are straightforward.

- Utilize NOAA NSRS tidal benchmarks for future vertical reference—including RTK base.
- If needed, run levels from the NOAA NSRS benchmark to the Corps benchmark. Add Corps benchmark to NSRS.
- Model the project MLLW datum using existing NOAA gauge data.
- Develop/publish a tidal-geoid model for the project.

A cost estimate will follow the same format and simulated rates as the above estimate.

Contract Administration

USACE hired-labor, technical S&A, coordination with NOAA, A-E, in-house (Project Manager)	3 MD @ $800/MD	$2400
USACE hired-labor, technical (H&H, Engineering, etc)	3 MD @ $800/MD	$2400
USACE hired-labor, CT admin charges		$7500
USACE hired labor & travel (site recon) (Proj Mgr)	1 MD @ $800/MD	$ 800
	Travel	$ 500
	TOTAL	$13600

A-E Contract Line Items

Run levels from NSRS benchmark to USACE benchmark (RTK base)

Mob/demob to project site [CD]	2 CD @ $2500	$5000
Set/level/describe 5 tidal benchmarks	1 CD @ $2500	$2500
Process, Blue Book, transmit data to NOAA	3 MD @ $800	$2400
A-E Project Manager S&I	1 MD @ $1500	$1500
	TOTAL	$11400

Data Processing and Reporting

Develop new interpolated tidal model (In-House H&H or A-E)	1 MD @ $800	$ 800
Develop MLLW-geoid file for project	1 MD @ $800	$ 800
USACE or A-E hired-labor to update documents & files	1 MD @ $800	$ 800
	TOTAL	$2400

Summary

Contract Administration	$13600

A-E Contract Line Items	\$11400
Data Processing and Reporting	\$ 2400
Subtotal	\$27400
Contingencies @ 15%	\$ 4110
TOTAL BUDGET ESTIMATE	**\$31500**

A major line item in the above estimate is the \$11.4K to run a one-mile level line and input this data into the NSRS. If the NOAA tidal benchmark can be used as a RTK base station, then this line item could be eliminated, along with the associated A-E contract administration costs (\$7.5K). This would reduce the budget estimate to the \$10K level. Alternatively, this level line could be included in the next Project Condition Survey scope.

C-27. Estimating Cost Avoidance for Navigation Projects on Superseded Tidal Epochs

Navigation projects that have not been updated to the latest tidal epoch will have, for much of CONUS, deepened grades due to sea level rise. Correcting these projects to the current NOAA tidal epoch will reduce the amount of maintenance dredging on the next cycle—varying from 0.1 ft to more than 0.5 ft depending on the magnitude of sea level rise. This will be offset somewhat for projects never updated from MLW to MLLW datum. It is also possible that more refined CEPD tidal modeling of the MLLW reference will modify the project grade. In effect, this CEPD updating process may result in reduced dredging on some projects; thus, a cost savings (or avoidance) from this CEPD effort. These cost avoidances (positive or negative) should be estimated for navigation projects and included as a line item in the project reports—Appendix D. If the project is already on the latest tidal epoch and MLLW datum model, then no benefits would be reported.

Only a rough estimate of should be developed during the CEPD assessment. To simplify the estimate, assume the entire project area is maintained rather than the actual maintained shoaling areas; thus, there is no need to pull out contract drawings to assess the percentage of the project area routinely maintained. Obviously, the estimate is inflated if only small portion of project is maintained, or significant portions are naturally below grade. This can be offset by assuming a low unit price (cost/CY). However, if entire project were ever deepened, then a higher percentage of the project grade would be excavated. Note that this computation represents a one-time cost avoidance—once the project is adjusted to the correct epoch and MLLW datum model, no savings would result after the first maintenance dredging cycle. Reduced dredging will result each time epochs are updated by NOAA, assuming continuing sea level rise.

The cost avoidance can be simply estimated given a channel length, width, epoch change, and cost/CY:

Estimated volume = length (ft) x width (ft) x Δ_{epoch} (ft) ÷ 27 cy/ft3

Estimated cost reduction = Estimated volume x $/CY

As an example, we will use Mullet Key Cut in Jacksonville District's Tampa Bay, FL Project:

Dimensions: 22,000 ft long x 600 ft wide channel
Currently on 1960-1978 epoch ... $\Delta_{epoch} = 0.2$ ft
Assumed unit price of maintenance dredging: 10 $/CY

$$\text{Volume} = 22{,}000 \cdot 600 \cdot 0.2 \div 27 \text{ CY / ft}^3 \approx 100{,}000 \text{ CY}$$

$$\text{Estimated Cost Reduction @ 10 \$/CY} \approx \$1 \text{ M}$$

(Projected over the entire 60-mile project, this small 0.2 ft adjustment would equate to approximately $10M to $20M in reduced excavation cost if the project were ever deepened from 43/45 ft to 50 ft and the entire project area required deepening.)

C-28. Application of GPS in Measuring Surface Elevations on Navigation Projects

Once a definitive tidal model of a project's tidal MLLW datum, epoch, and local range variations has been established, and RTK elevation measurement is implemented to eliminate the tidal phase errors, then local ellipsoidal and geoidal variations in the RTK elevation measurement process need to be accounted for. These variations (or undulations) are shown in the following figures.

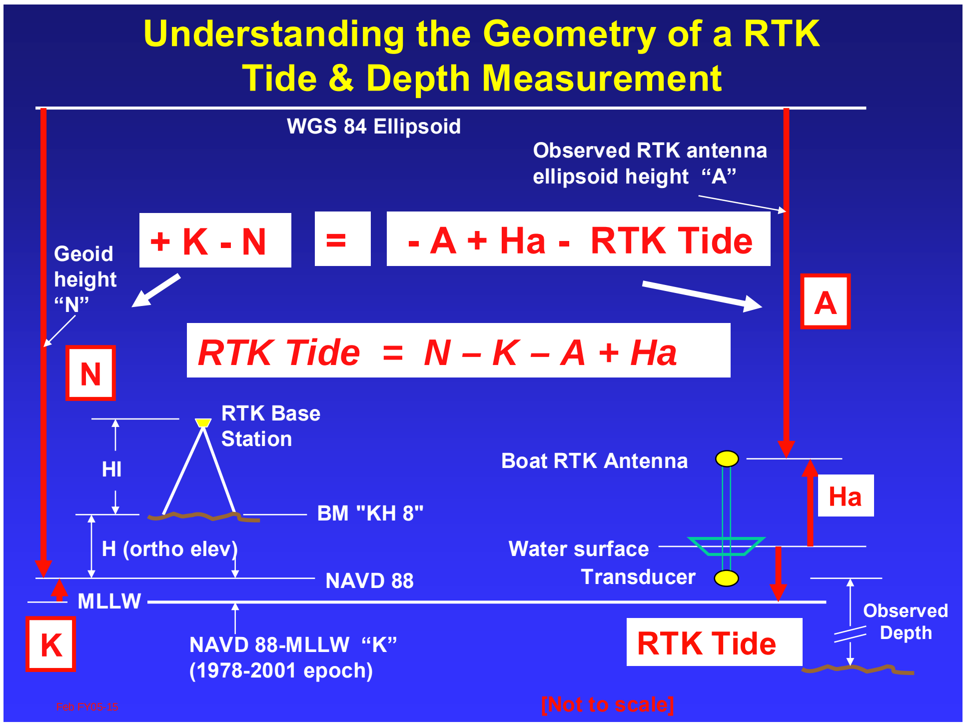

Figure C-24. RTK Tide Measurement--Basics

Figure C-24 describes the basic geometry of a RTK tide elevation measurement. The elevation of the water surface is measured using GPS measurements relative to the ellipsoid, which ranges some 50 to 100 feet above MLLW in CONUS.

The above figure "assumes" the MLLW datum elevation ("K") is constant over the region. It also "assumes" the height to the ellipsoid (geoid height "N") is constant. This is rarely the case in practice, as shown in Figure C-25 below.

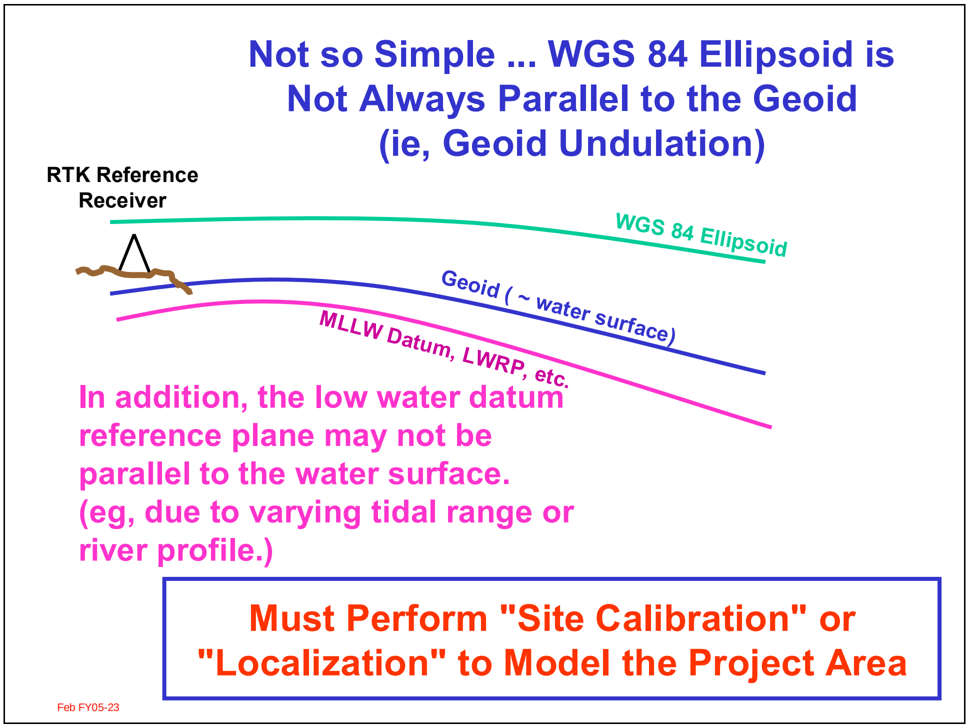

Figure C-25. Ellipsoid and MLLW datum undulations

As shown Figure C-26, a model of both the MLLW datum and ellipsoid/geoid is needed to effectively use RTK elevation measurement methods. Once developed, this model provides an absolute, defined correction surface for all users (dredging, surveying, etc.—a "KTD" file) in a navigation project, and eliminates the need for the inaccurate extrapolation of tidal gauge observations to remote project sites. Tidal phase errors and MLLW datum variations are effectively eliminated as long as the modeled MLLW-geoid variations are applied by all users—i.e., all use the same "site-calibration" "site localization" model. (MLLW datum variations are minimized by the tidal hydrodynamic model and are thus eliminated by rigidly fixing/calibrating the model to the tidal gauges). The only observational error is that of the RTK calibration process itself since the MLLW-geoid model used in the RTK elevation solution is assumed to be absolute.

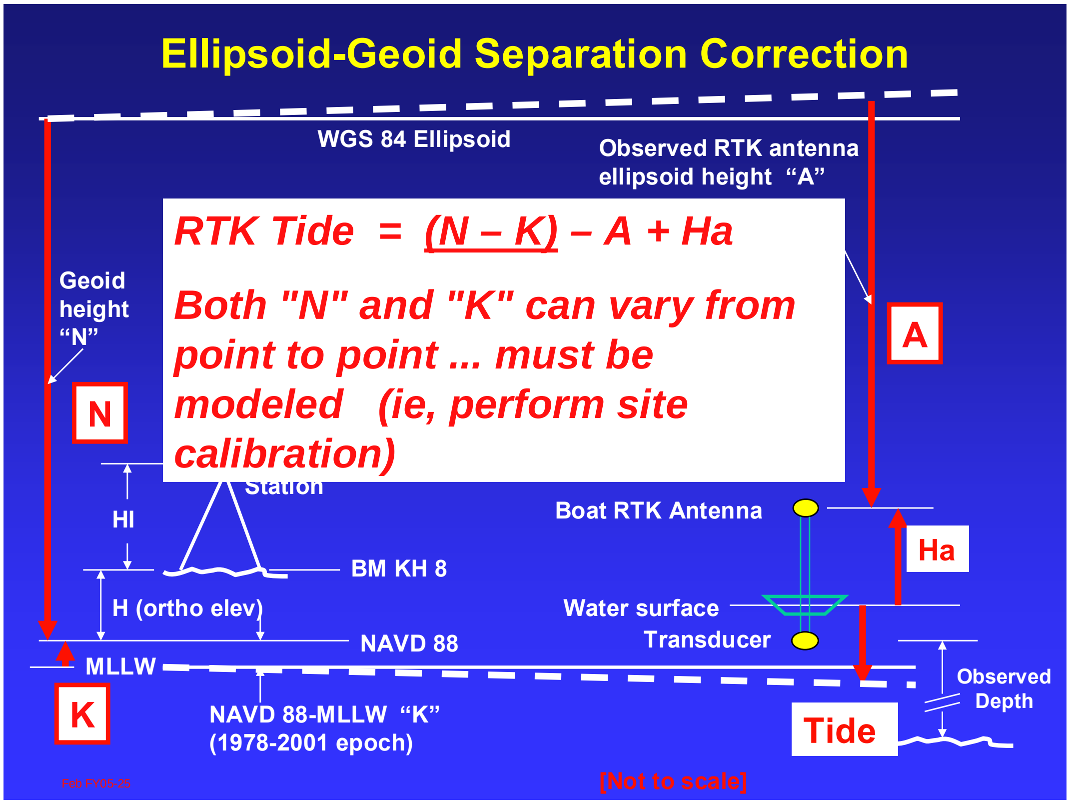

Figure C-26. Ellipsoid-Geoid-MLLW corrections

The tidal or combined tidal-geoid model ("KTD" file) is typically rectilinear rather than linear along a channel. A post spacing of every 100 or 500 ft is recommended. The resolution should be to the nearest 0.01 ft. An example of such a model is shown in Figure C-27 below.

RTK elevation observations cannot be relied on without performing periodic checks at the reference/base station (and hopefully at other points if available). As shown in Figure C-28, a tide staff is set near the RTK base station and RTK-derived tidal measurements are verified (and calibrated) against the gauge/staff reading.

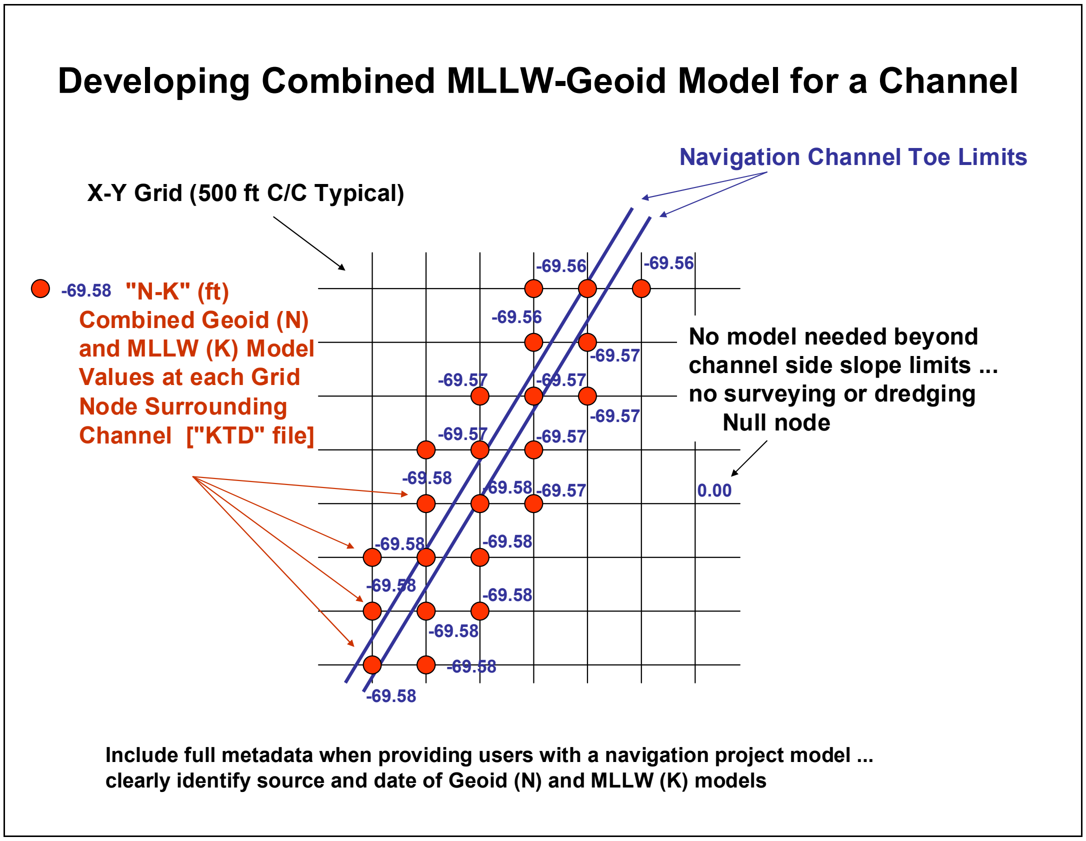

Figure C-27. MLLW-Geoid Model for RTK corrections

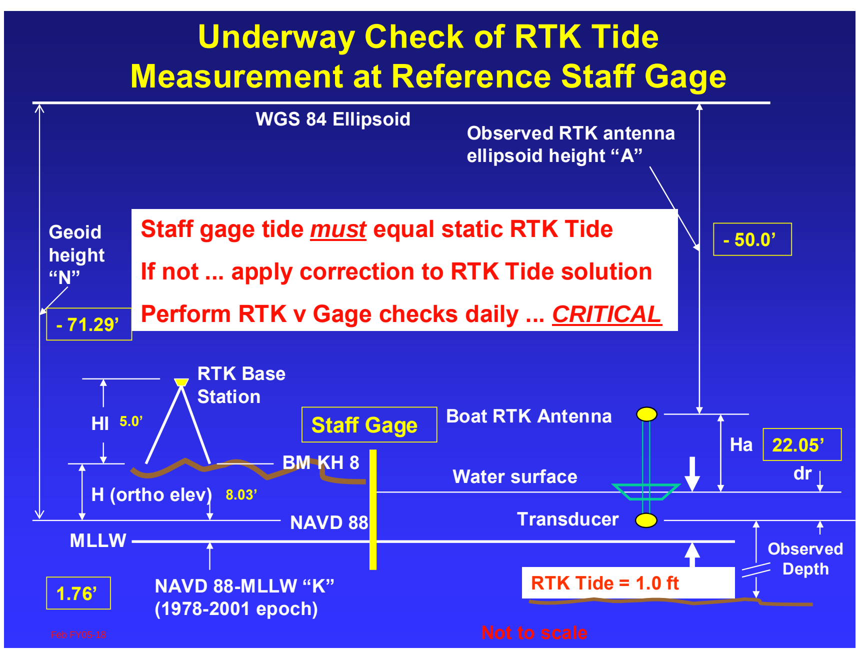

Figure C-28. RTK Quality Control (calibration) checks